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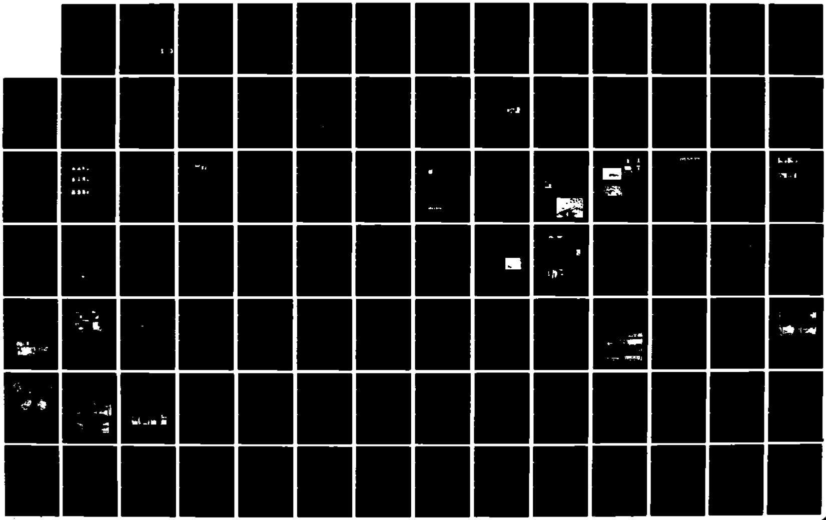

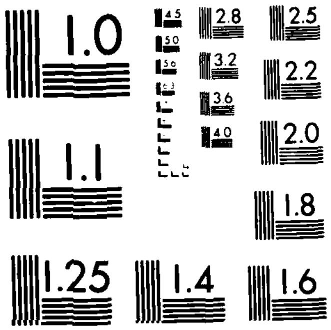

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Review of Aircraft Crash Structural Response Research

Emmett A. Witmer
David J. Steigmann

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August 1982

US Department of Transportation
Federal Aviation Administration
Technical Center
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16. Abstract

A review of aircraft crash structural response research has been carried out by studying the literature, discussions with researchers working in that area, and visits to facilities/personnel involved in conducting and/or monitoring aircraft crash structural response investigations. Aircraft structures consisting of conventional built-up metallic construction and those consisting of advanced composite materials were of interest. The latter type of materials and construction is of particular interest since their use is expanding rapidly, and crashworthiness of such structures is of increasing importance.

Some recent theoretical and experimental studies of the behavior of composite-material structures subjected to severe static, dynamic, and/or impact conditions are noted. Such topics as crashworthiness testing of composite fuselage structures, the impact resistance of graphite and hybrid configurations, and the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems are reviewed.

The principal theoretical methods for predicting the nonlinear transient structural responses of severely loaded structures are reviewed. Available lumped-mass and finite-element computer programs tailored to aircraft crash response analysis are noted.

A review is made of some current and planned research to investigate experimentally the mechanical failure, postfailure, and energy-absorbing behavior of a sequence of composite-material structural elements and structural assemblages subjected to static loads or to simulated crash-impact loads.

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Unclassified	Unclassified	133	

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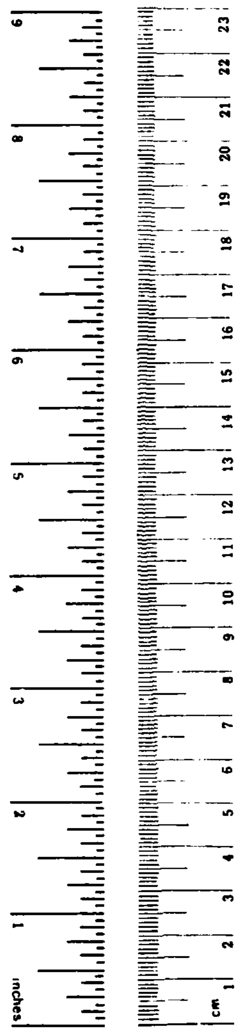
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

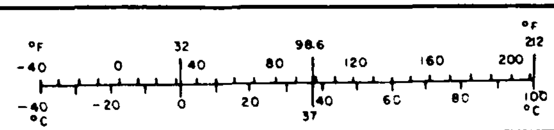
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This research was carried out by the Aeroelastic and Structures Research Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Mass. 02139 under Supplement No. P00010 of AFWAL Contract F33615-77-C-5155. The technical monitors were David Nesterok and R. Garcia of the FAA Technical Center, Atlantic City Airport, New Jersey. The advice, guidance, and cooperation of these individuals are acknowledged most gratefully.

For helpful advice and information, the authors are indebted to M. Card, H. Carden, R. Hayduk, J. Housner, H. McComb, J.H. Starnes, and R. Thomson of the Structures Division, NASA-Langley; to B. Dexter and G. Farley working at the Process/Applications Branch, Materials Division of NASA-Langley; to R. Burrows, G.T. Galow, and T. Mazza of AVRADCOM, Ft. Eustis, Va.; and to J.D. Cronkhite of Bell Helicopter Textron. All of these individuals were helpful in providing information on past, current, and planned research on aircraft structural response under static and/or crash conditions, simulated or actual.

The authors much appreciate the permission granted to reproduce in full herein four well-written and informative summary papers on past, current, and/or future crash-response research. Reproduced in Subsection 2.1 is the paper "Investigation of Crash Impact Characteristics of Composite Airframe Structures" [20] by J.D. Cronkhite et al by permission of the American Helicopter Society. The papers by Thomson and Goetz [11] and Thomson and Caiafa [2] are reproduced in Subsections 2.2 and 2.3, respectively, by permission of the authors. Also reproduced in Subsection 2.3 is the paper by Wittlin [21] by permission of the author and the Lockheed-California Company.

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SUMMARY

A review of aircraft crash structural response research has been carried out by studying the literature, discussions with researchers working in that area, and visits to facilities/personnel involved in conducting and/or monitoring aircraft crash structural response investigations. Aircraft structures consisting of conventional built-up metallic construction and those consisting of advanced composite materials were of interest. The latter type of materials and construction is of particular interest since their use is expanding rapidly, and crashworthiness of such structures is of increasing importance.

Some recent theoretical and experimental studies of the behavior of composite-material structures subjected to severe static, dynamic, and/or impact conditions are noted. Such topics as crashworthiness testing of composite fuselage structures, the impact resistance of graphite and hybrid configurations, and the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems are reviewed.

The principal theoretical methods for predicting the nonlinear transient structural responses of severely loaded structures are reviewed. Available lumped-mass and finite-element computer programs tailored to aircraft crash response analysis are noted.

A review is made of some current and planned research to investigate experimentally the mechanical failure, postfailure, and energy-absorbing behavior of a sequence of composite-material structural elements and structural assemblages subjected to static loads or to simulated crash-impact loads. These structures consist of beams, frames, fuselage keelson, tubes, etc. with either discrete stiffening or sandwich stiffening, utilizing graphite-epoxy, Kevlar-epoxy, and/or other fibrous composite combinations. Plans for drop-impact tests of full-scale composite-material fuselage sections with skin, frame, subfloor, seat and seat-restraint systems are noted. An associated program of structural response predictions and comparisons with measurements is expected to validate and upgrade those prediction capabilities. These research efforts are intended to expand the data base for improving the crashworthy design of composite-material aircraft structures and to improve dynamic structural response predictions and analytical/design tools.

Some recommendations for further work are offered.

SECTION 1

INTRODUCTION

1.1 Study Objectives

Innovative design and the use of a variety of structural and supplementary materials have been undergoing continuous development for decades in order to enhance the survivability of occupants of various types of civilian and military vehicles when subjected to severe loads encountered in crash, impact, blast, and other dangerous conditions. Many governmental agencies and industrial organizations have sponsored and/or conducted studies designed to improve the state of knowledge concerning the transient response and damage suffered by both the vehicle structure and the occupants under these severe loading conditions. This, in turn, has led to the development and use of crashworthy design procedures and/or requirements for certain classes of vehicles: aircraft, automotive, rail, etc. Some of the material utilization and design concepts developed are applicable to a variety of vehicles, but many others are tailored to the specific type of vehicle involved. The basic physics of crash and impact phenomena in the (low) impact velocity regime of interest in these situations are common to all of these various vehicles.

With the accelerating use of advanced composite materials in military, commercial, and general aviation aircraft as well as in the automotive industry, there is an increasing need to develop a better understanding of the behavior of composite-material structures under crash and impact conditions which are representative of aircraft (and automotive) crash situations.

While much work has been done both experimentally and theoretically on the severe transient structural responses of conventional built-up metallic aircraft structures (which absorb a considerable amount of energy as they deform and fold), much less information and experience have accrued on the behavior of advanced composite aircraft structures under these postulated severe environmental conditions. Hence, it is timely to review and assess this overall problem to summarize the state of knowledge (both theoretical and experimental) for these <u>two generic types</u> of aircraft structures, with the <u>principal objective</u> being to identify the key unresolved problems which must be addressed to improve our understanding of the <u>crash dynamics of aircraft structures which utilize a significant amount of composite material in structural regions which can undergo severe structural responses</u>.

Recently the Federal Aviation Administration Technical Center prepared a comprehensive report and plan of research on aircraft crashworthiness applicable to both built-up metallic and composite-material aircraft [1]*. Included in that research plan were essentially four categories of crash-

* Numbers in square brackets [] denote references given in the reference list at the end of the text of this report.

worthiness problems:

a. Airframes
b. Cabin Safety: Seat/Restraint Systems and Interior Furnishings
c. Fuel System Protection
d. Emergency Evacuation Systems

The study carried out and documented in the present report does not address items c and d at all; it pertains principally to item a with some discussion of item b.

In 1981, Thomson and Caiafa [2] wrote an excellent summary of past, present and planned research on aircraft crashworthiness. The reader is urged to consult Ref. 2 for a clear, concise and comprehensive discussion of the highlights of aircraft crashworthiness work.

In 1979, Cronkhite, Haas, Berry, and Winter of Bell Helicopter Textron under sponsorship by the U.S. Army Research and Technology Laboratories (AVRADCOM) reported a study [3] of the crash-impact characteristics of advanced airframe structures. Reviewed in that report are many details on both experiments and prediction methods for investigating the behavior of basic structural components and/or structural assemblages under severe deformation conditions (static and/or dynamic). That study included both built-up metallic and advanced-composite-material structures. The crashworthiness state of the art reported then largely prevails today, but with some updates which have occurred in the intervening period. Also, the research recommendations set forth in Ref. 3 remain pertinent at this time.

The present report seeks to summarize the crashworthiness state of the art today but in a more specialized and less comprehensive fashion than given in Refs. 1, 2, and 3.

1.2 Overall Research Approach

The present state-of-the-art review of crashworthiness was carried out by conducting a literature search and study, and by visiting (because of time and fund constraints) only a few of the many organizations experienced in relevant work. These steps are described briefly in the following two subsections.

1.2.1 Literature Search

Since MIT Aeroelastic and Structures Research Laboratory personnel have been involved actively for more than 25 years, in both experimental work and analysis method developments for various types of simple and complex structures undergoing severe nonlinear transient response behavior, the MIT-ASRL library and files contain many relevant reports and papers -- both internally and externally generated. These were reviewed. In addition, the MIT libraries contain many pertinent books, journals, proceeding, etc. -- covering many years and including the most recent editions; a catalog search was made and documents were obtained for study.

In the early stages of this study, FAA Technical Center personnel gave and/or loaned pertinent reports to the MIT-ASRL personnel. Also, the U.S.

Army Research and Technology Laboratories sent us some documents from their extensive past work on aircraft crashworthiness.

At MIT we conducted a NASIC library search for documents on crash research and crashworthiness for aircraft and automobiles, crash simulation, crash models, and composite materials. Abstracts of some 710 publications were printed out and checked to identify useful documents. Among those documents considered to be pertinent and useful in the present review, about one-half had already been seen and studied. We sought to obtain the remainder for study.

In studying the various documents retrieved, additional interesting references were noted. As many of these as feasible were sought and/or obtained for study.

In addition, telephone discussions were held with various individuals working on crashworhiness (NASA-Langley, AVRADCOM, Bell Helicopter Textron,...).

1.2.2 Facility Visits

Advice, guidance, and crashworthiness information from FAA Technical Center personnel were sought and obtained during two visits to the FAA Technical Center -- on Sept. 4, 1981 and again on April 16, 1982. Discussions were held principally with R. Garcia, D. Nesterok, and C. Nuckolls.

On Jan. 27, 1982 we visited the Structural Mechanics Branch of the NASA Langley Research Center to become more familiar with the very extensive crashworthiness work already conducted so ably at that facility and of planned future crashworthiness related work. Various structures and impact test facilities at NASA-Langley were visited. NASA-Langley personnel gave us a stack of pertinent documents for study, and generously shared their experience and views on crash response matters pertaining to both built-up metallic aircraft structures and composite-material structures. Effective design concepts for cabin floors/substructure as well as seats/restraints were discussed and illustrated with example hardware. The paucity of crash response experimental data for many structural components and/or assemblies composed of composite material was noted. Many unanswered questions remain. NASA-Langley personnel involved in parts of these discussions included:

M. Card	R. Hayduk	H. McComb	R. Thomson
H. Carden	J. Housner	J.H. Starnes	

During these discussions, it was noted that various design features found to be effective in enhancing crash survivability have been identified in the NASA-Langley studies, and certain aircraft operators or manufacturers have adapted these features to improve crash survivability of specific general aviation aircraft which employ "conventional construction."

On Jan. 28, 1982, we met with R. Burrows, G.T. Galow, and T. Mazza at the U.S. Army Research and Technology Laboratories (AVRADCOM), Ft. Eustis, Virginia. The extensive work already carried out by AVRADCOM and its principal contractors was reviewed. Crew or occupant survivability in helicopter crashes has been a primary concern. Crash alleviation features included in the landing gear system, the fuselage subfloor, and stroking seats have enhanced crash survivability. The upcoming construction and impact testing of full-scale composite-material fuselages are expected to provide better insight into the crash responses of these advanced types of structures. The Advanced Composite Aircraft Program of AVRADCOM is expected to include crash response assessments as an important aspect. Experience to date indicates that fiberglass composite "covers" offer better abrasion resistance than do Kevlar or G/E "covers." The use of Kevlar in sandwich type construction is effective where crash survivability and alleviation are desired. AVRADCOM personnel provided a number of reports on their and sponsored crash response work for subsequent study.

On March 23, 1982, a visit was made to the Air Force Materials Laboratory and to the Aeronautical Systems Division, Wright-Patterson AFB, Ohio. Discussions were held with Dr. S.W. Tsai and Dr. R.Y. Lim (of the University of Dayton Research Institute) at the AFML, and with J. Lincoln and W. Dunn at the ASD.

Drs. Tsai and Lim discussed experimental studies of failure mechanisms for various types of laminated composites and exhibited many specimens which illustrated these failure modes. Fatigue and creep studies for simple composite structures were reviewed, some ongoing experiments were demonstrated, and related papers and reports were provided.

Mr. Lincoln and Mr. Dunn outlined the current Air Force crash loads requirements and described recent studies of survivable accidents. Air Force emphasis is on flight safety practices, minimization of landing/takeoff crash effects by terrain smoothing adjacent to runways, wing root integrity, and the use of self-sealing fuel tanks, foams, and fire extinguishers.

1.3 Structural Crash Response Overview

Interest in understanding and alleviating the effects on vehicle occupants of crashes has been active for many years. The work of DeHaven reported in 1944 [4] was pioneering, identified key items that contributed to injuries in aircraft crashes, and offered guidelines for improving the crashworthiness of light aircraft. Subsequently, these guidelines were applied in the design of specialized light aircraft. Since then, many organizations (NACA, U.S. Army, FAA, NASA,...) have conducted and/or sponsored a succession of studies to develop the state of knowledge concerning vehicle crash response for a wide variety of civilian and military aircraft, and such work is being pursued vigorously at the present time.

Similarly, the automotive industry and cognizant federal agencies such as the National Highway Traffic Safety Administration have been carrying out detailed studies of crash response for a variety of vehicles and components since about the mid 1960's.

Common to both aircraft and automotive vehicle crash response have been considerations of survivable environmental conditions, human tolerance acceleration-time-direction levels, load-limiting concepts, intrusion limitations, structural component crashworthy design and integration, and fire prevention measures, including fuel containment. In the following, however, discussion will be limited to structural response behavior --

under "survivable" conditions -- the other cited topics are beyond the scope of the present study.

To assist in identifying the principal structural response and failure behavior under crash conditions, full-scale crash tests [5,6] were conducted by the FAA on a DC-7 and a Lockheed L-1649 aircraft in 1964 at the Flight Safety Foundation facility in Phoenix, Arizona. Later in the 1972-1980 time period, various types of full-scale light aircraft, a CH-47 helicopter, and aircraft fuselage sections were crash tested at the Impact Dynamics Research Facility of the NASA Langley Research Center [7,8,9,10]. Acceleration, strain, and photographic instrumentation (interior and exterior) as well as post-morten studies provided transient response, failure, and post-failure data; data from instrumented dummies provided "transmitted acceleration-time" information. In some cases the vehicles were caused to impact upon concrete surfaces at appropriate combinations of impact incidence angle and impact velocity. In other cases, impact against a packed dirt surface to simulate conditions in a plowed field was employed. These tests permitted observing,under many realistic but controlled conditions, representative types of transient and failure response, but various secondary effects such as aircraft overturning, cartwheeling, or tree and obstacle impact were not covered in these studies [11].

Since the late 1950's [3], the U.S. Army has been carrying out an effective and comprehensive study of crash behavior of Army aircraft, accident data, and concepts to improve crashworthiness. Highly important crashworthiness developments were made, and this work resulted in the Crash Survival Design Guide [12] which subsequently has been revised and updated [13-17]. Those guidelines are used by aircraft designers to meet criteria spelled out in MIL-STD-1290(AV) for Light Fixed-and-Rotary-Wing Aircraft Crashworthiness [18]. This has resulted in a very substantial improvement in aircraft crashworthiness performance and occupant survival in the field. This development program included an extensive Army Flight Safety and Helicopter Crash Testing Program [19] and a program of laboratory tests.

Similarly, under the auspices of the National Highway Traffic Safety Administration various organizations have conducted a wide variety of crash tests on many different types of vehicles and structures. Extensive photographic and other instrumentation provided data to identify the principal types and sequences of structural failure and crush-up present in each of many vehicle/structural systems. This led to innovative designs for load-limiting and appropriate energy management histories to enhance occupant survival. All of this work has been supplemented by laboratory tests of structural components and assemblages under static and (sometimes) dynamic conditions. Many of the automotive manufacturers have conducted similar very extensive research the results of which are reported in part in the open literature.

The aircraft and automotive crash/impact experiments have involved structures which can be characterized conveniently in two categories: (1) built-up metallic structures (assemblages) and (2) composite-material (non-metallic) structural components and/or assemblages; of course, combinations of these two types of structures are common in many of today's vehicles. Built-up metallic structures "fail" typically in some mode of buckling and then can undergo a considerable amount of deformation and strain (and energy absorption) before local structural rupture occurs. On the other hand composite-material structures may "fail" initially in many different possible modes, but typically undergo a relatively small amount of straining before structural rupture occurs. Thus, composite-material structures often behave in a "relatively brittle" fashion and soak up energy rather poorly; however, innovative structural concepts and material combinations can be effective [2,3] in absorbing crash/impact energy and alleviating the attendant transient response effects.

1.4 Report Organization

Section 2 is devoted to a concise description of the status of aircraft crash research in three categories: (a) helicopters, (b) general aviation aircraft, and (c) transport aircraft. Work in category "a" has been carried out largely by USAVRADCOM and its contractors while the FAA and NASA have conducted studies in categories "b" and "c" together with their contractors.

Recent studies on the behavior of composite materials and structures under static and impact conditions are reviewed in Section 3.

In addition to extensive experimental static and dynamic nonlinear structural impact-crash response studies,both in the laboratory and in the field, a considerable effort has been made to develop theoretical methods for predicting nonlinear crash-impact structural responses of both conventional metallic and composite-material structures. These prediction methods often are designed to focus on certain subsystems of the overall system. In some cases a part of the overall system is modeled crudely while the particular (connected) subsystem of particular interest is modeled with a relatively high degree of fidelity. Since vehicles of interest consist of many different structural arrangements and configurations each of which requires specific and appropriate modeling, it is feasible here to review only the two basic types of modeling and analysis employed: (a) simplified lumped-parameter and hybrid modeling and (b) more refined finite-element and hybrid modeling. These matters are discussed in Section 4 for both complex built-up metallic structures and for composite-material structures.

Crash-response research which is needed, as perceived by various organizations and individuals in both governmental agencies and industry, is discussed in Section 5. Noted are the general goals of crash response research as well as several current and planned crash response research investigations pertinent to helicopters, general aviation aircraft, and transports as well as to basic airframe structures. Some suggestions for additional research are offered.

Finally, a summary of the present review study and some resulting conclusions concerning the current and planned programs of crash response research are given in Section 6.

SECTION 2

STATUS OF AIRCRAFT CRASH RESPONSE RESEARCH

Authoritative and comprehensive but concise reports on the status of aircraft crash and crash-response research have appeared in the past few years. This work pertains to helicopters, general aviation aircraft, and transport aircraft. The earlier phases of those studies dealt with vehicles of conventional built-up metallic construction, but in the past decade emphasis has focused upon aircraft structures and structural concepts employing advanced composite materials which promise greater structural efficiency and durability with lower costs. Also sought for composite-material aircraft is "a degree of crashworthiness at least equal to its replaced built-up metal counterpart".

Crash-response characteristics of airframe structures of both metallic and advanced composite construction with emphasis on helicopter applications have been described in an excellent comprehensive paper by Cronkhite, Haas, Winter, Cairo, and Singley [20]; this was followed by a more detailed report by Cronkhite, Haas, Berry, and Winter [3]. Extensive laboratory and field experiments, analysis method developments, and design concept studies are reported; this pioneering work was supported by the U.S. Army Research and Technology Laboratories (and its predecessors).

Studies by NASA and the FAA on the crash response behavior of general aviation aircraft have been summarized in a clear comprehensive fashion by Thomson and Goetz [11] and by Thomson and Caiafa [2]. Laboratory tests, full-scale crash tests, and analysis method developments are reviewed.

Thomson and Caiafa [2] also discuss past and current studies of transport aircraft crash behavior as well as planned future research in this area, including transport aircraft structures composed of advanced composite material. Many aspects of transport aircraft crash response and crash effects are reviewed. Here also laboratory tests of structural elements and assemblages, under both static and crash-impact dynamic conditions as well as a full-scale field crash test of a fully-instrumented B-720 transport aircraft, are being employed to develop a fuller understanding of aircraft crash response and to lead to improved aircraft crashworthiness and occupant survival.

Wittlin [21] has summarized an extensive series of past crash-response studies and transient response analysis developments pertaining to helicopters and light fixed-wing aircraft. He also has summarized current studies being conducted for the FAA and NASA on transport crash response problems by Lockheed, Boeing, and Douglas; this comprises an early phase of a comprehensive transport crash response research effort planned by the FAA and NASA. These studies strive to identify categories of potentially-survivable crash conditions and the principal structural and systems aspects which influence occupant response and survival. Wittlin demonstrates the role and effectiveness of a lumped-parameter simulation model for analyzing the crash responses of helicopters, light aircraft, and transport aircraft.

Since the state of knowledge on aircraft crash response as described in Refs. 2, 3, 11, 20, and 21 is essentially as it exists today, and those descriptions are all written in a concise and lucid but comprehensive fashion, the present authors believe that a redescription and paraphrasing of the contents of those papers would not be nearly as useful to the reader as these complete papers themselves. Also, it is felt that a "redescription and translation" of those papers would result in the omission of key insights, crash response experience, and other useful background data which enriches one's appreciation of aircraft crashworthiness problems. Therefore, permission has been requested to reproduce those papers in full in this report for the reader's convenience.

Accordingly, the paper by Cronkhite et.al. [20] with emphasis on helicopters is reproduced in Subsection 2.1; that by Thomson and Goetz [11] on general aviation aircraft is reproduced in Subsection 2.2; and those by Thomson and Caiafa [2] and Wittlin [21] which include discussions of current and planned transport crash response research are reproduced in Subsection 2.3.

2.1 Helicopters

The kind permission of the American Helicopter Society for the reproduction of the following paper presented originally at the 34th Annual National Forum of the American Helicopter Society, Washington, D.C. in 1978 and subsequently in the October 1981 issue of the Journal of the American Helicopter Society is acknowledged most gratefully.

Investigation of the Crash Impact Characteristics of Composite Airframe Structures

J. D. Cronkhite, T. J. Haas
Bell Helicopter Textron

R. Winter, R. R. Cairo
Grumman Aerospace Corporation

G. T. Singley, III, USAAVRADCOM

PRESENTED AT THE 34th ANNUAL NATIONAL FORUM OF THE AMERICAN HELICOPTER SOCIETY WASHINGTON, D.C. MAY 1978

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USAAVRADCOM

Abstract

The results of a joint Bell/Grumman contracted effort with the Army are discussed. The effort was directed toward the investigation of the crash impact characteristics of advanced troop transport helicopter airframe structures constructed of composite materials. Currently available information was surveyed on the crash impact behavior of composite materials, analytical tools for design of crashworthy airframe structures and airframe structure crashworthiness design criteria. Information on the crash impact behavior of composite materials was found to be limited. An automotive study showed that by innovative design, composite materials could function efficiently as energy absorbers to reduce crash impact loads. Other pertinent studies were found that are currently in progress at Bell Helicopter Textron, the NASA Langley Research Center and the U. S. Army's Research and Technology Laboratories and are summarized. Finally, effects of composite materials on the compliance of airframe structures with current Army crashworthiness requirements are discussed.

Introduction

In recent years, composite materials such as graphite, fiberglass, boron and Kevlar have been used more extensively in the design of aircraft components, both structural and nonstructural. It is reasonable to assume that the helicopter industry will have large numbers of production aircraft with major structural components, such as the fuselage, wings, empennage, blades or landing gear, constructed of composite materials in the near future. Entire composite airframes have already been produced for general aviation type aircraft. It will therefore benefit the industry to have an understanding of the behavior of composite materials in a crash environment before large numbers of production aircraft are in the field.

Presented at the 34th Annual National Forum of the American Helicopter Society, May 1978.

Two fundamental guidelines to consider when designing the airframe structure for crash impact are first, that a protective shell be maintained around the occupied area and second, that the structure be crushable and absorb energy, thus reducing deceleration forces on the occupants and large masses. These and other crashworthy design considerations are summarized in Figure 1. When considering the application of composites to a crashworthy airframe structure, it is known that these materials generally exhibit a low strain-to-failure characteristic behavior compared to metals. Ductile metals such as 2024 aluminum can tolerate rather large strains, deform plastically, and absorb considerable energy without fracture or separation. Because of this characteristic of composites, energy absorption will probably not come through an inherent stress-strain behavior as it can with metals, but rather through innovative design configurations. These configurations will provide for energy absorption and force attenuation by other means; for example, the protective structural shell can be surrounded by a crushable material such as foam, honeycomb or a crushable composite concept.

Extensive crashworthiness studies for metal aircraft structures have been conducted in the past. For example, early in 1960 the U. S. Army Transportation Command (now USAAVRADCOM) initiated a long-range program to study aspects of crashworthiness which culminated in the issuance of a crash survival design guide and the associated military standard (References 1 and 2). Research into the crashworthiness and energy absorption aspects of aircraft structures was initiated in the mid 1960's with studies conducted at General Dynamics-Convair and Dynamic Science making prime contributions to the understanding and analysis of the energy absorption characteristics of airframe structures (References 3, 4 and 5).

In order to place this investigation in the proper time perspective, it should be noted that the lag between the initiation of research into airframe impact energy absorption and its incorporation

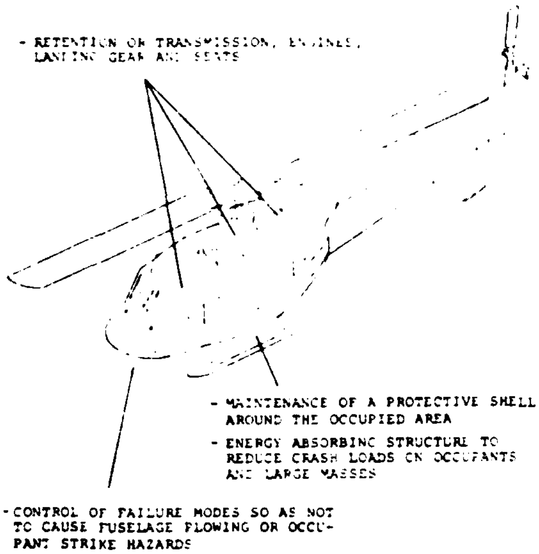


Figure 1. Helicopter fuselage crashworthiness design considerations.

into a design, such as the UTTAS, has been on the order of 8 - 10 years. Therefore, this investigation represents the initial effort toward designing a crashworthy composite airframe structure in the mid 1980's.

The objectives of this investigation are the following:

1. Survey the literature and determine the existing data base on the crash impact behavior of composite materials.

2. Review current analytical methods used for the design of crashworthy airframe structures and assess their suitability for analysis of composite structures.

3. Review current crashworthiness design criteria for military and commercial utility helicopter airframe structures to determine its application to a composite airframe structure.

Behavior of Composite Materials

Literature Survey

The first step in this part of the investigation was to survey existing literature on the behavior of composite materials in a crash environment. The data bases used in the survey were:

1. The National Technical Information Service (NTIS)

2. The Defense Documentation Center (DDC)

3. The Engineering Index (Compendex)

4. "ORBIT (SDC)

5. "DIALOG" (Lockheed)

A flow diagram of the literature search methodology used to retrieve information from data bases and other sources is shown in Figure 2. To access a data base, NTIS for example, blocks of keywords are formed and input to the system so that all information pertinent to the particular topic in question can be retrieved. Keyword blocks are then combined to further focus the search on the subject being surveyed. The number of references found under keyword blocks and various combinations of keywords is presented in Figure 3. Combinations of keywords and a summary of the literature found under each combination are discussed in the following paragraphs.

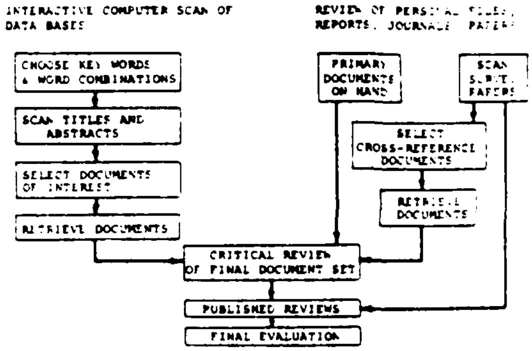
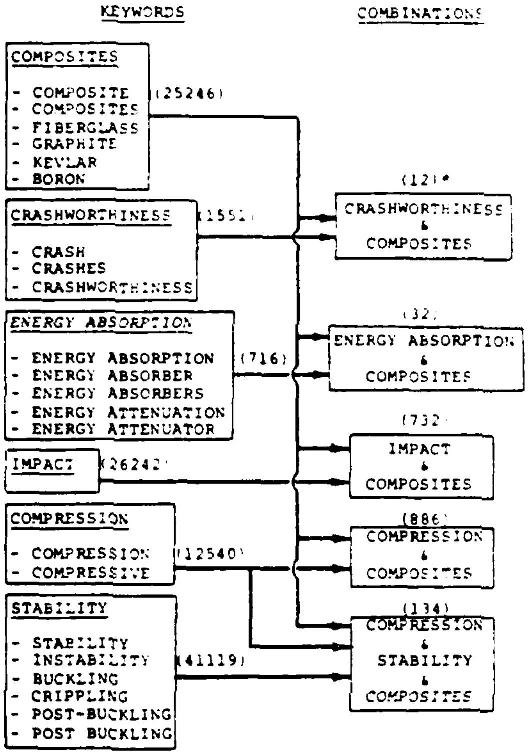


Figure 2. Literature survey methodology.



* NUMBERS IN PARENTHESES INDICATE NO. OF AVAILABLE REFERENCES

Figure 3. Literature survey results from combinations of keywords.

Crashworthiness/Composite Materials

Twelve documents were located under the combination of the two keyword subjects "crashworthiness" and "composite materials". A visual examination of the 12 documents did not disclose any published reports specifically on the application of composite materials to an airframe structure for a crash environment.

Two of the documents reported on molded chopped fiberglass components that were fabricated and tested for use as a highway median barrier and as an instrument panel glare shield (References 6 and 7). The tests of the highway barrier concluded that it would prevent vehicles from penetrating or crossing the median while also minimizing their rebound and lowering their deceleration rates below 6g. The tests of the glare shield showed it reduced decelerations from 300g to 60g; however, its failure produced sharp edges which could cause a head injury.

There are two reports about automobiles that were fabricated in whole or part using fiberglass construction and tested in a crash environment (References 8 and 9). The automobile tested by the Budd Company was a 1974 Pinto two-door sedan which was modified by replacing the front fenders and lower longitudinal frames with fiberglass/polyurethane foam sandwich panels and tubes. The panels and tubes were intended to attenuate the crash forces which occur during a front-end collison (Figure 4). A series of static and dynamic tests were conducted on the tubular and panel specimens prior to retro-fitting the contact automobile to validate the concept. When the automobile was tested by impacting a barrier at 50 mph, the tubes and panels attenuated the crash forces until a premature failure occurred in a tube due to off-axis loading. This illustrates the potential problem with directional energy absorbers that off-axis loads can result in failure of the device and make it ineffective.

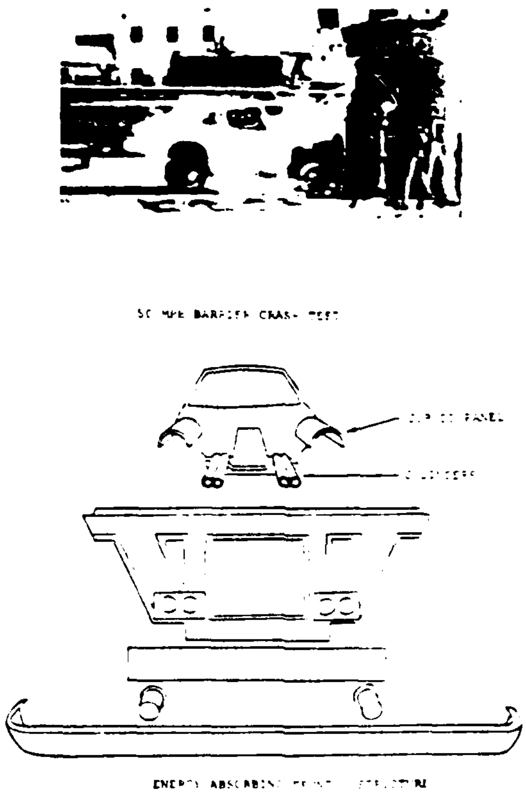


Figure 4. Crash test of composite front end automobile.

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The conclusion of the Budd Company was that the fiberglass reinforced plastic sandwich structure was superior to the solid laminate structures tested by others for energy absorption. They also concluded that a composite structure could be formulated which would be satisfactory in a crash environment if designed properly.

Several general aviation type aircraft have used composite construction, but referenceable documents on the accident and crash experience with these aircraft could not be found in the literature or through the FAA.

At least two helicopter composite fuselage design studies have been conducted in which crashworthiness was addressed. These were the preliminary design studies of medium utility transport (MUT) helicopters conducted for the Army by Boeing-Vertol and Sikorsky (References 10 and 11). Although crashworthiness was addressed, the primary emphasis was placed on optimizing basic design concepts, cost, weight and producibility.

Energy Absorption/Composite Materials With the exception of the automobile tests, the use of composite materials as energy absorbers or attenuators has been limited to low velocity impact applications such as bumpers (References 12, 13 and 14). There has been work on improving the energy absorption characteristics of composite materials at the micro or local structural level, but no correlation has been drawn between this research and its application in a crash environment.

Impact/Composite Materials There has been a great deal of research in the area of impact strength of composite materials but this research has been mainly directed toward local impacts produced by tool drops, foreign objects, missiles and particles. Although damage due to a local impact can compromise the compressive failure mode of a structure, the techniques used in determining this damage are not applicable to a crash impact involving gross structural deformations.

Compression Failure Mode/Composite Materials During a crash, the compression failure modes of the structure influence the energy absorption and crash impact behavior of the design. The work that has been done on metal structures has sought to predict and improve the post-buckling characteristics of the airframe structure, thereby increasing the energy absorbed during a crash (Reference 15).

The results of some tests conducted by General Dynamics-Convair to measure the load deflection characteristics of various aluminum plate-stringer panel configurations are shown in Figure 5. Note that the load deflection behavior of the integrally stiffened panel is poor in comparison to the rolled stringer sections because the failure mode was an explosive fracture. Also note that the load at initial failure was higher; this translates to higher inertia forces transmitted to the occupants and to the large mass items during a crash impact.

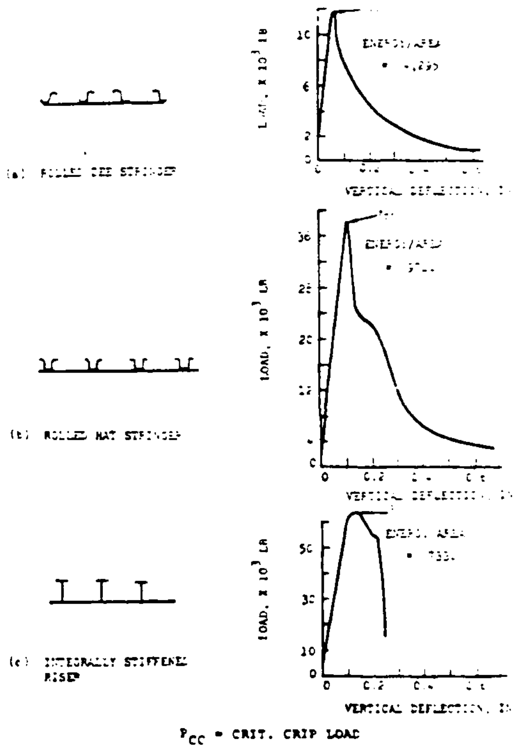

Figure 5. Load-deflection curves for various aluminum sheet/ stringer panels.

In contrast to the work done on metallic structures, the research on the compression failure modes of composite materials has been concerned with predicting the static allowable load of a structural element. Some test results of typical research on compression failure modes are shown in Figure 6. The researchers were primarily interested in the post-buckling characteristics of these specimens and increasing the static allowable load and not the total load-deflection or energy absorbing characteristics of the structures.

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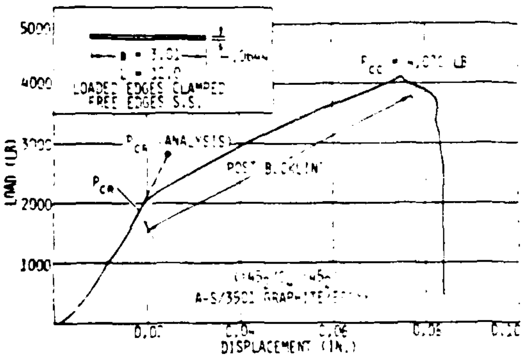

Figure 6. Load-deflection curve for graphite/epoxy plate (*Reference 40*).

Topics for Further Investigation

Static and fatigue behavior, analytical techniques, environmental effects, manufacturing, processing, and nondestructive evaluation techniques have received sufficient attention to support the application of composites in helicopter advanced structures. However, the survey revealed several topics which will require considerable attention before reliable, lightweight, crashworthy, advanced composite helicopter structures can be designed. For purposes of this discussion, these topics can be summarized under two major categories: supportive data necessary for analytical crash prediction and supportive data for the vehicle design.

The data necessary to support analytical crash prediction should include topics such as structural evaluation, material characterization, and failure analysis. The crash environment also needs to be better defined in terms of structural attitude, expected strain rates, and the time sequence of events. This will help establish the criteria for the analytical simulation and specific material characterization. To fill the gaps in the current data base, characterization of the materials should be performed at the expected strain rates for crash impact and should be in terms of the energy absorption capabilities of laminates and cores. This characterization should also include the post-buckling behavior of the laminated composite structures. The area of failure analysis needs additional attention because of the complex failure modes of laminated structures for crash impact loading. This complexity results not only because of the heterogeneous, anisotropic nature of these materials, but also because of complications which also affect the static performance of the structure such as manufacturing defects, cure cycle variation, lamina stacking sequence and part geometry. Fracture and failure prediction techniques need to be revised to correlate with observed failure modes.

The supportive data necessary for vehicle design development should include topics such as the crash impact response of structural configurations and materials, the survey of crashed advanced composite field components and the assessment of the crash impact response compared to current metal helicopter structures. The crash impact response of the candidate structural components has to be obtained through test or analysis before their effect on the overall vehicle response can be assessed. Particular emphasis should be placed on the crashing behavior of the structural elements and the fracture and fragmentation behavior which is peculiar to composites.

This investigation was concerned with the structural aspects of crashworthiness, but the subject of flammability and the hazards associated with the thermal decomposition of polymeric composites during a post-crash fire should receive further attention. In particular, what is needed is a study of the noxious gas and smoke evolution during the polymer thermal decomposition. Emphasis should be placed on the variables which affect decomposition and the determination of the human tolerance levels to the by-products.

Another side issue which may affect the response of a composite material structure in a crash environment is that of service life degradation. Since the static properties of composite structures can be affected by factors such as low energy impacts (e.g., dropped tools, landing site stores) and moisture absorption or desorption, it is logical to expect the crash impact properties may also be similarly affected.

Review of Analytical Methods

The recent interest in vehicle crashworthiness has motivated the development of a number of mathematical crash simulation computer programs. These simulations can provide a means of evaluating the effectiveness of vehicle structures in satisfying a set of crashworthiness criteria, such as the Army's MIL-STD-1290 (Reference 2). At their best, such computer programs can be used as a tool in the design process in which crashworthiness is a new structural requirement in addition to those which already exist for static strength, fatigue resistance, dynamic response, and (battle) damage tolerance.

As part of this study, an investigation was made to determine the usefulness of currently available plastic, large deformation structural crash simulations; especially those which can be applied to airframe structures of composite materials. This investigation was aided substantially by previous surveys of the crash simulation literature, particularly those done by Saczalski (Reference 16), McIvor, et al (Reference 17) and Kamat (Reference 18).

Use can be made of a mathematical crash simulation during the design process as shown in Figure 7. The key elements in this process are a set of design criteria and a valid crash simulation method. Inputs of structural behavior, which take the form of stress-strain curves or component crush test data, are used to predict the structure's dynamic response. The crashworthiness of the design can then be evaluated against the criteria to determine if it is satisfactory or if a redeisgn is necessary. During this process, some simulations require the assumption of internal crush modes while others are used to predict them. It should be noted that experimental crash simulations can also be used, but because of cost factors, are probably best used for validating the final design as determined by the analytical methods.

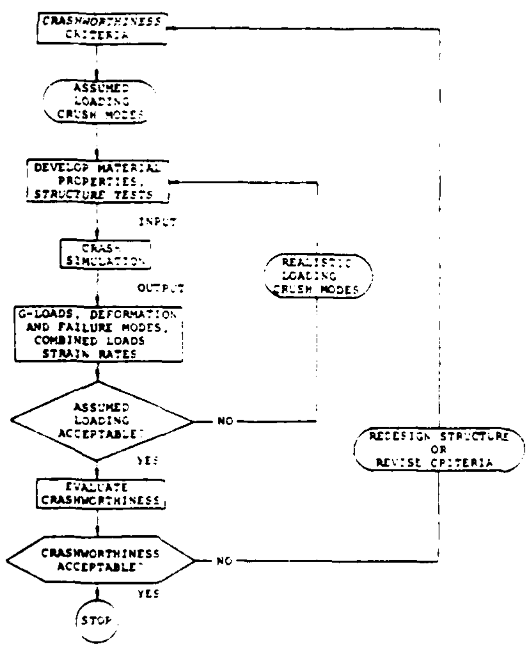

Figure 7. Computer crash simulation in vehicle design process.

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The main characteristics used for evaluating the functionality of the mathematical crash simulations were:

- Capability Level
- Structural Model
- Mathematical Type
- Convenience Features

Other features which were of secondary importance in this investigation were: the mass model, the terrain and barrier model, the external loads, and the numerical solution procedure.

For this study three broad categories of capability level were established, along with potential uses during design. They are as follows:

Simple Capability These simulations can be used to evaluate gross responses and design trends. They feature:

1. Large structural assemblies modeled as single crush elements
2. Up to 10 masses, 50 degrees-of-freedom (unknowns in motion equations)
3. *One or two dimensional geometry and motions*

Intermediate Capability These simulations can be used for studies of structural design parameters and energy dissipation in subassemblies. They feature:

1. Structural subassemblies modeled separately, no sheet/skin panel model
2. Up to 100 masses, 500 degrees of freedom
3. Two or three dimensional geometry and motions

Detailed Capability These simulations can be used for predicting failure or collapse modes, and redesigning individual components. They feature:

1. Individual structural components modeled separately, including sheet/skin panels
2. More than 100 masses, 500 degrees of freedom
3. Three dimensional geometry and motions

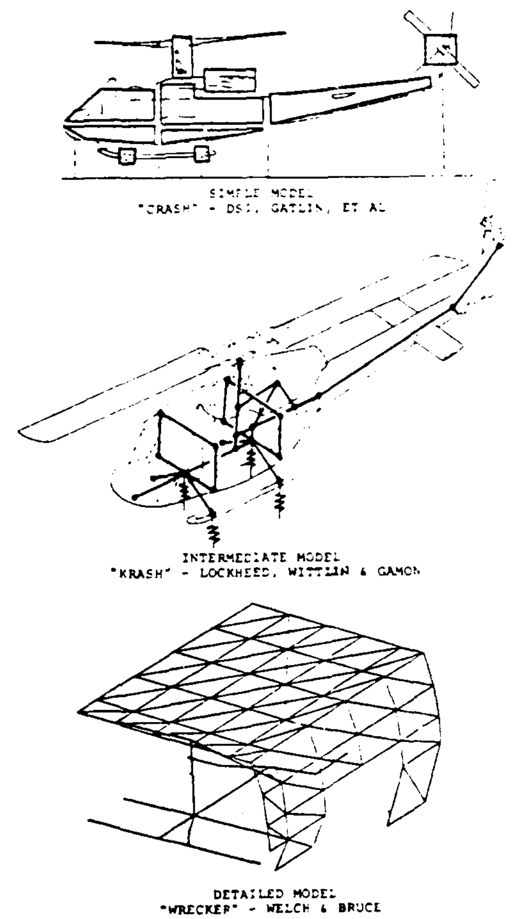

Figure 8. Examples of mathematical simulation capability levels.

Figure 8 shows specific examples of the capability levels of three mathematical crash simulations as applied to automobiles and rotary-wing aircraft.

Numerous simple capability hybrid simulations are available (References 19 through 24, for example). Of these, the two most notable programs are those authored by Herridge and Mitchell of Battelle Columbus Labs and by Gatlin, et al, of Dynamic Sciences, Inc. The work done by Herridge and Mitchell was directed toward automobile crash impacts, while that done by Gatlin, et al, examined the vertical impact of a helicopter fuselage. This latter program (informally called "CRASH") simulates the fuselage as rigid masses connected by nonlinear axial and rotary springs in a predetermined arrangement. Both of these simulations are two dimensional.

Of the intermediate capability programs, the most advanced, and perhaps the most widely used, hybrid simulation is "KRASH" by Wittlin and Gamon of Lockheed California Co. (References 25 and 26). "KRASH" utilizes a three-dimensional arbitrary framework of point masses connected by beams to simulate the fuselage structure. The remaining intermediate capability programs use finite element computer codes and include: Shieh's work at Calspan Corporation (Reference 27), "CRASH" by Young at Philco-Ford (References 28 and 29) and "UMVCS" by McIvor, et al, at the University of Michigan (Reference 30). Shieh idealizes the structure as a two-dimensional array of beams with yielding confined to the plastic hinges at their ends, while "CRASH" and "UMVCS" use three dimensional models of a framework of rods and beams. "UMVCS" could also be considered a hybrid because it requires test data input to define the moment rotation curves for the plastic hinges at the beam ends.

The detailed crash simulations are all three-dimensional finite element codes with the capability of modeling stringers, beams, and structural surfaces such as skins and bulkhead panels. The four codes currently available are: "WHAM" by Belytschko of Northwestern University (Reference 31), "WRECKER" by Welch, et al, of Illinois Institute of Technology (Reference 32), "ACTION" by Melosh, et al, of Virginia Polytechnic Institute of Technology and State University (Reference 33), and "DYCAST" by Pifko, et al, of Grumman Aerospace Corporation (References 34 and 35). "WHAM" currently can be used to idealize a structure which contains only isotropic material. It uses partly interactive yielding, i.e., neglects the effect of shear stresses on plasticity. "WRECKER" contains the same formulations as "WHAM" but also has the added convenience features of graphics and restart. "ACTION" also has partly interactive yielding, and it can be used only with a structure constructed with isotropic materials. Additionally, "ACTION" also contains an internally varied time step with numerical error controls. "DYCAST" can idealize a structure constructed of orthotropic material. Its features include: fully interactive yielding internally varied time steps with error control, restart, and graphic output.

A summary of the assessment of these specific crash simulations is given in Table 1. Note that the hybrid codes do not account for collapse or failure under com-

ITEM	HYBRID	FINITE ELEMENT
PLASTIC COLLAPSE & CRUSH	ALL	ALL
WITH COMBINED LOADS	NONE	ALL EXCEPT SHIEH'S
MATERIAL FAILURE	ALL	NONE
WITH COMBINED LOADS	NONE	NONE
SKIN & BULKHEAD	ALL (POORLY)	WRECKER, WHAM ACTION, DYCAST
ORTHOTROPIC LAMINATES	ALL	DYCAST
CORED SANDWICHES	ALL	NONE
BEAM CROSS-SECTION DEFORM /CRIPPLING	ALL	NONE
JOINT DEFORM. & FAILURE	ALL	NONE
STRAIN RATE STIFFENING	KAMAL HERRIDGE	WRECKER
WITH LOCAL VARIATIONS	NONE	WRECKER

Table I. Computer Crash Simulations Assessment.

bined loads, because the crash data inputs are derived from tests with a single load. All of the finite element codes, with the exception of Shieh's, can account for multiple load components. The crush test can furnish the hybrid computer codes with data to analyze orthotropic laminates and core-sandwich panels, while only "DYCAST", of the finite element codes, can analyze an orthotropic material, and none of the evaluated finite element codes can currently analyze a core sandwich. "WRECKER" is the only one of these codes which will account for strain rate effects in a logical way by determining the local strain rate and adjusting the stiffnesses. All the hybrids can account for joint failure and crippling, because these effects are part of the crush test data.

The major conclusions of this investigation on computer crash simulations for advanced material applications are:

1. That there is not a single existing code that is satisfactory
2. That hybrid codes are theoretically incomplete.
3. That finite element codes currently lack sufficient advanced material capability.

The recommendation for current crash simulations on advanced materials is to use "KRASH" with applicable crush test data for the preliminary parametric studies and gross evaluations. For a detail design, "DYCAST" can be used for analyzing orthotropic laminates. However, this code is still under development and has not yet been experimentally verified. It is not currently possible to perform an extensive detailed design evaluation of a structure with sandwich core construction. This type of construction seems to hold promise for increased energy dissipation with advanced composites.

Research in Progress

During the survey of the current data base of information on the crash impact behavior of composite structures, some pertinent research in-progress was found that has not yet been documented or made available to the public. The three areas of research in-progress that will be discussed are:

1. The NASA Langley study of airframe crashworthy design concepts for general aviation aircraft.
2. The Bell Helicopter testing of energy absorbing cylinders.
3. The Army testing of stiffened cylinders and helicopter fuselage structure sections.

Airframe Crashworthy Design Concepts

A joint FAA and NASA research program is in progress at Langley Research Center to develop valid, practical structural design criteria and improve crashworthiness design technology. The total program is shown in Figure 9. NASA, under the direction of R. Thomson, Crash Safety Program Group Leader, is conducting full-scale crash tests of light fixed wing aircraft, developing analytical techniques and evaluating crashworthy design concepts for seats and airframe structures.

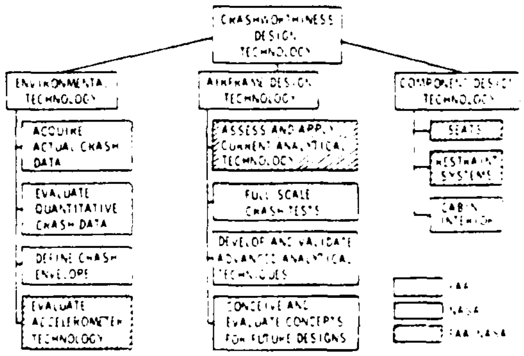

Figure 9. Joint FAA/NASA aviation crashworthiness program.

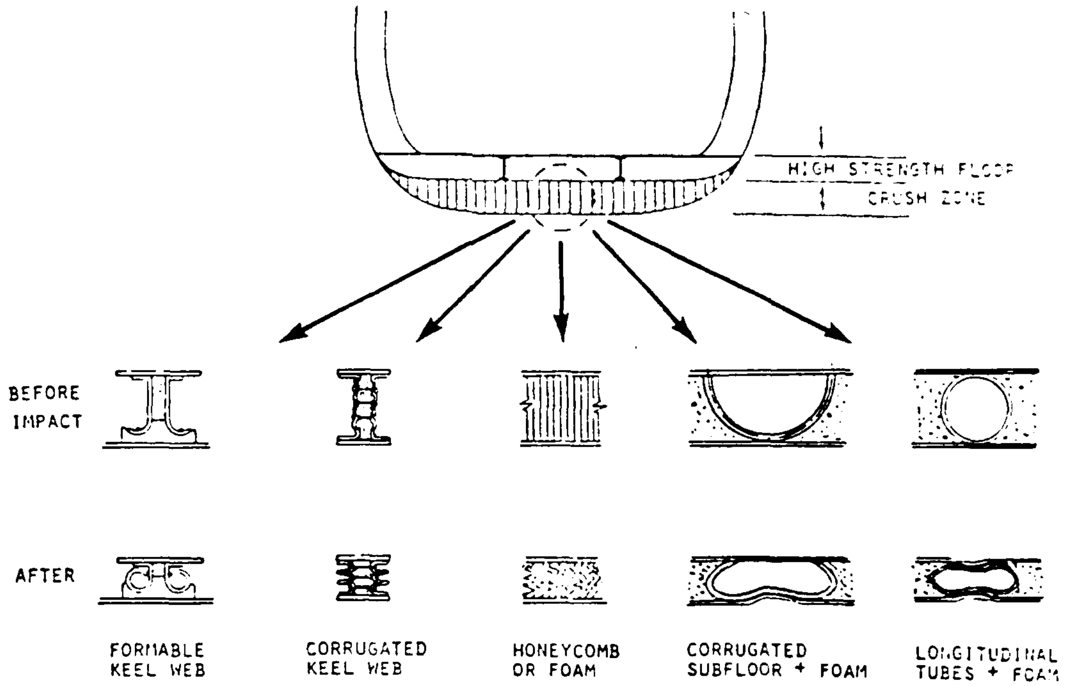

Figure 10. Energy absorbing materials in lower fuselage.

Bell Helicopter is currently under contract with NASA to develop crashworthy design concepts for the fuselage structure of light aircraft. The primary emphasis is on concepts applied to future airframes constructed of metal, but consideration is also being given to concepts applicable to composite structures.

Energy absorbing concepts that can be applied to the lower fuselage structure are currently being designed and will be tested later. Crushable material in the lower fuselage is being designed to attenuate crash forces, absorb energy and distribute loads to the primary structural shell. Typical examples are shown in Figure 10. Concepts applicable to composite structures are shown in Figure 11.

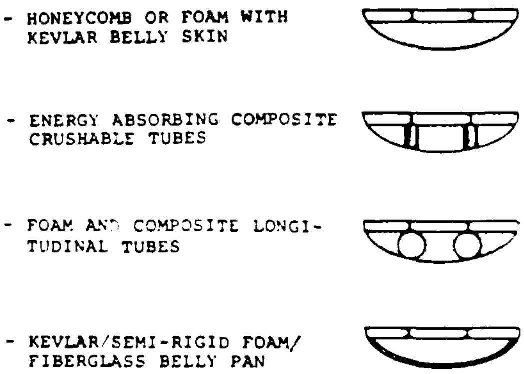

Figure 11. Energy absorbing concepts for composite fuselage structures.

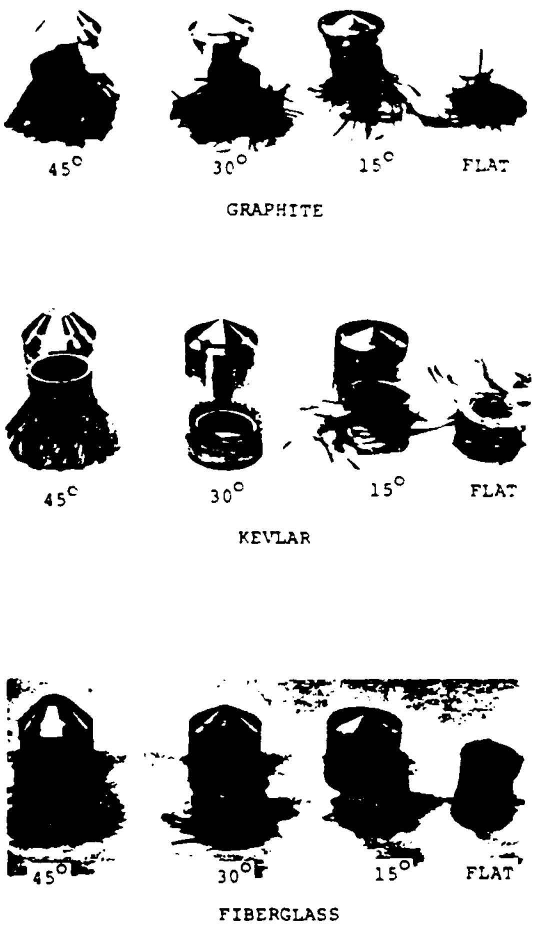

Figure 12. Static crush tests of composite tubes for various anvil angles.

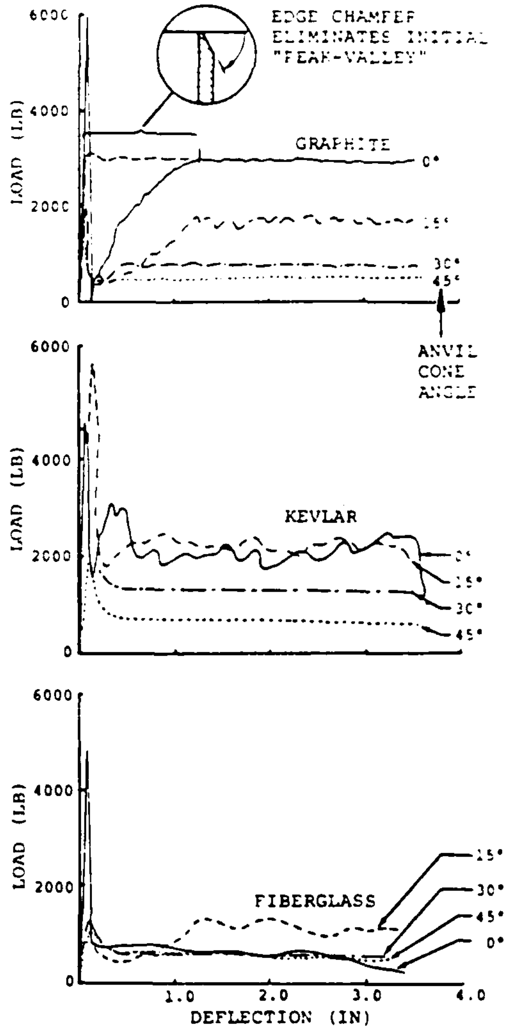

Figure 13. Load-deflection curves for energy absorbing composite tubes.

Composite Tube Energy Absorbers

When discussing composite fuselage structures, it generally is assumed that some other material is needed for energy absorption, but there does not appear to be any specific information available to support this assumption. Bell therefore conducted a study to investigate the energy absorption characteristics of some simple composite material deformation concepts. Composite tubes were designed with equivalent static strengths and filament wound at ±45° angles from three materials: graphite/epoxy, Kevlar/epoxy, and fiberglass/epoxy. These tubes are shown in Figure 12 after being crushed on coned anvils.

The specimens were statically and dynamically tested and exhibited good energy absorption characteristics with progressive failure and a flat, rectangular shaped load-deflection curve as shown in Figure 13.

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The highest specific energy absorption for the tubes shown in Figure 12 was obtained with the graphite/epoxy tubes crushed on a flat (0°) surface and was above 15000 (ft-lb/lb). It is felt that since these were only preliminary tests this value can be significantly improved by optimizing parameters such as fiber orientation. Specific energy absorption values of 40000 (ft-lb/lb) have already been obtained with improved fiber orientation using graphite/epoxy tubes.

Tests of Composite Structure Sections

The Research and Technology Laboratories (RTL) of the U. S. Army Aviation Research and Development Command (USAAVRADCOM) have been working on two test programs related to the crash impact behavior of composite structures. The first program is to develop standard testing methods for comparison of the response of different materials to crash type loading and the second program is to conduct static and dynamic compression testing of scale helicopter fuselage type sections.

R. L. Foye of the Advanced Systems Research Office of RTL, Ames Research Center has conducted compression tests of stiffened cylinders in an attempt to develop an economical method of testing materials assembled in a manner representative of an aircraft structure (Reference 36). The stiffened cylinders were approximately 9 inches in diameter by 18 inches in length and had four equally spaced longerons. Specimens of aluminum, fiberglass, Kevlar and graphite have been tested.

For the aluminum specimen, Foye noted that the compression failure modes typical of aircraft structures were in evidence: local skin buckling, progressive skin buckling over the entire surface, local crippling of each stiffener, bending of the skin and stringer, complex creasing and folding, fastener tearout, skin puncture and skin tearing. This indicates the merit in the test method since it exercises the compression failure modes known to occur in metal. The results of tests to date indicate composites configured similar to metal specimens have lower energy absorption than metal and produce splintering and more separation of the stringers from the skin. Figure 14 shows that the energy absorption for composite specimens was about 1/5 to 1/6 that of aluminum. Foye's goal is to develop a standard test method that can be achieved for about one thousand dollars per test sepcimen. More tests are planned with different types of loading in the future.

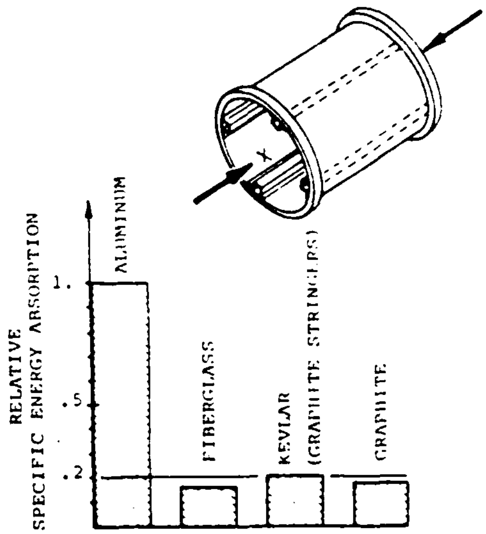

Figure 14. Specific energy absorption comparisons of composite stiffened cylinders to metal.

During the program sponsored by the Applied Technology Laboratory (ATL) of RTL and documented in Reference 15, Lockheed analyzed and tested (static and impact) several aluminum structural specimens representative of typical helicopter lower fuselage structure. These specimens were approximately 1/2 the size of the UH-1H lower fuselage bulkhead and stiffener arrangement beneath the transmission pylon support, except that the skin, web and angle stiffeners were full scale. The failure modes and post-failure behavior of this structure are of interest since vertical crash loads are transmitted through it to the transmission pylon structure. The current ATL test program is to investigate the behavior of similar composite structures subjected to the same static and impact conditions. Because specimens of the size tested by Lockheed could not be accommodated by the existing ATL drop tower, a dimensional analysis was performed, and the validity of conducting the tests using specimens 1/2 the scale of the Lockheed specimens was verified by one static and two drop tests. The aluminum honeycomb concept of Figure 15 has also been static and impact tested (14 ft/sec impact velocity). This concept weighs 8.6% less and has a Specific Energy Absorption, $\left(SEA = \frac{\text{Energy Absorbed}}{\text{Structural Weight}}\right)$, 1.82 times that of the baseline aluminum specimen. Future testing is planned with specimens constructed of composite materials, e.g., graphite/epoxy and fiberglass.

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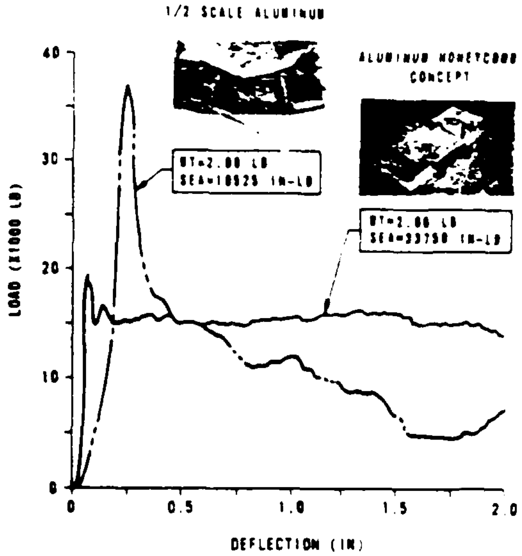

Figure 15. Load-deflection curves for half-scale structure sections.

Crashworthiness Design Criteria

There are many considerations in the design of a crashworthy airframe structure. For this investigation, only those that relate to the crash impact characteristics of airframe structures constructed of composite materials will be discussed. These crashworthy design considerations are as follows:

1. Maintaining an airframe protective shell for occupant protection
2. Providing tiedown strength to react the applied inertia forces to large mass items
3. Designing for breakaway airframe structure to reduce the total mass
4. Reducing occupant strike hazards within the cabin area
5. Absorbing energy by fuselage crushing
6. Reducing post-crash hazards
7. Designing for failure modes

Discussions of crashworthy design considerations can be found in the Army's Crash Survival Design Guide (Reference 1) and many other sources, for example, References 15, 37, 38, and 39.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AIRFRAME PROTECTIVE SHELL	●	●		●
BREAKAWAY AIRFRAME STRUCTURE	●			
OCCUPANT STRIKE HAZARDS	●			
ENERGY ABSORPTION	●			
POST CRASH HAZARDS	●			
FAILURE MODES	●			
INERTIA FORCES TIEDOWN STRUCTURE	●	●	●	●

Figure 16. Airframe structure crashworthiness criteria and current design criteria.

These design considerations have been addressed in civilian and military regulations, standards and specification wherein they have been formulated into criteria. A summary of available criteria and the crashworthy design considerations addressed by each is presented in Figure 16.

By far the most comprehensive crashworthiness requirements document is MIL-STD-1290 (Reference 2). MIL-STD-1290 establishes minimum crashworthiness design criteria which, when implemented in the initial stages of aircraft systems design, will provide aircraft possessing improved crash safety characteristics. This standard was based on the design guidelines of the Crash Survival Design Guide. Because these criteria represent a needed capability, crash impact survivability, modification of this criteria in any manner that would reduce the level of crash protection to be provided was not considered. Although some of the material properties of composites run counter to the material properties preferred for crashworthy structures (e.g., low ductility, fracture, and splintering), nothing learned in this investigation indicates that the crashworthiness of MIL-STD-1290 cannot be met with structures constructed from composite materials. On the contrary, the aforementioned Budd Co. automotive effort with fiberglass/polyurethane foam sandwich panels and tubes indicates that crashworthy composite structures are possible through innovative design. Certainly satisfying the crashworthiness guidelines shown in Figure 1 with composite structures is challenging; however, available R&D results indicate that the challenge is not so much one of simply meeting the criteria, rather it is how to do so without significantly compromising the benefits of composites (e.g., weight and cost savings) and how to analytically substantiate compliance with the criteria. Whereas substantiation of airframe crashworthiness is based on scores of full scale crash tests, numerous section tests, and available analytical techniques, this investigation has shown that little analytical or experimental effort has been performed on the crashworthiness of composite airframes.

Conclusions

Conclusions that can be drawn from this investigation of the crash impact behavior of composite materials are as follows:

1. Very little pertinent data exists on the crash impact behavior of composites. The pertinent information that was found can be summarized as follows:

   - The automotive work done by the Budd Company indicates composite structures can be crashworthy if proper emphasis is placed on crashworthiness early in the design process; also, foam sandwich construction improves the energy absorption compared to solid laminate construction.

   - Preliminary tests by the Army indicate that when composite structures are constructed in a manner similar to metals, they exhibit lower energy absorption, more fractures, peeling and splintering than metals.

   - The Bell and automotive studies indicate that composites progressively crushed exhibit good energy absorption characteristics.

2. There is considerable data on basic strength, projectile impact and foreign object damage (FOD) of composite materials, but this data does not pertain to crash impact.

3. Computer analysis methods are still being verified for metal structures, while composites will need special treatment because of their brittle failure characteristics.

4. There is some research in-progress by the Army, NASA, and Bell directed towards investigation of the crashworthiness of composite aircraft type structures.

5. Although some of the composite material properties and impact behavior of composites on a structural element level are apparently not favorable to crashworthiness, there is evidence that crashworthy helicopter structures constructed from composites are feasible through innovative design.

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2.2 General Aviation Aircraft

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NASA/FAA General Aviation Crash Dynamics Program—A Status Report

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NASA/FAA General Aviation Crash Dynamics Program—A Status Report

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The objective of the Langley Research Center general aviation crash dynamics program is to develop technology for improved crash safety and occupant survivability in general aviation aircraft. The program involves three basic areas of research: controlled full-scale crash testing, nonlinear structural analyses to predict large deflection elasto-plastic response, and load attenuating concepts for use in improved seat and subfloor structure. Both analytical and experimental methods are used to develop expertise in these areas. Analyses include simplified procedures for estimating energy dissipating capabilities and complex computerized procedures for predicting airframe response. These analyses are being developed to provide designers with methods for predicting accelerations, loads, and displacements of collapsing structure. Tests on typical full-scale aircraft and on full- and subscale structural components are being performed to verify the analyses and to demonstrate load attenuating concepts.

Introduction

IN 1972, NASA embarked on a cooperative effort with FAA and industry to develop technology for improved crashworthiness and occupant survivability in general aviation aircraft. The effort includes analytical and experimental work and structural concept development. The methods and concepts developed in this ongoing effort are expected to make possible future general aviation aircraft designs having enhanced survivability under specified crash conditions with little or no increase in weight and acceptable cost. The overall program is diagramed in Fig. 1. NASA's responsibility in this joint program is shown by shaded boxes, the FAA's role by unshaded boxes, and joint efforts by cross-hatched boxes.

Crashworthiness design technology is divided into three areas: environmental, airframe design, and component design. The environmental technology consist of acquiring and evaluating field crash data to support and validate parametric studies being conducted under controlled full-scale crash testing, the goal being to define a crash envelope within which the impact parameters allow human tolerable acceleration levels.

Airframe design has a twofold objective: to assess and apply current, on-the-shelf, analytical methods to predict structural collapse; and to develop and validate new and advanced analytical techniques. Full-scale tests are also used to verify analytical predictions, as well as to demonstrate improved load attenuating design concepts. Airframe design also includes the validation of novel load limiting concepts for use in aircraft subfloor designs.

Component design technology consists of exploring new and innovative load limiting concepts to improve the performance of the seat and occupant restraint systems by providing for controlled seat collapse while maintaining seat/occupant integrity. Component design also considers the design of nonlethal cabin interiors.

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Index categories: General Aviation; Structural Design; Structural Dynamics.

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Langley's principal research areas in the joint FAA/NASA crash dynamics program are depicted in Fig. 2. These areas include full-scale crash testing; nonlinear finite element analysis; seat, occupant, and restraint simulation; and energy absorbing seat and structural design concepts. Subsequent sections deal with these topics.

Full-Scale Crash Testing

Full-scale crash testing is performed at the Langley Impact Dynamics Research Facility[1] shown in Fig. 3. This facility is the former Lunar Landing Research Facility modified for free-flight crash testing of full-scale aircraft structures and structural components under controlled test conditions. The basic gantry structure is 73 m (240 ft) high and 122 m (400 ft) long supported by three sets of inclined legs spread 81 m (267 ft) apart at the ground and 20 m (67 ft) apart at the 66 m (218 ft) level. A movable bridge with a pullback winch for raising the test specimen spans the top and transverses the length of the gantry.

Test Method

The aircraft is suspended from the top of the gantry by two swing cables and is drawn back above the impact surface by a pullback cable. An umbilical cable used for data acquisition is also suspended from the top of the gantry and connects to the top of the aircraft. The test sequence is initiated when the aircraft is released from the pullback cable, permitting the aircraft to swing pendulum style into the impact surface. The swing cables are separated from the aircraft by pyrotechnics just prior to impact, freeing the aircraft from restraint. The umbilical cable remains attached to the aircraft for data acquisition, but it also separates by pyrotechnics before it becomes taut during skid-out. The separation point is held relatively fixed near the impact surface, and the flight path angle is adjusted from 0 to 60 deg by changing the length of the swing cable. The height of the aircraft above the impact surface at release determines the impact velocity which can be varied 0 to 26.8 m/s (60 mph). The movable bridge allows the pullback point to be positioned along the gantry to insure that the pullback cables pass through the center of gravity and act at 90 deg to the swing cables.

To obtain flight path velocities in excess of 26.8 m/s (60 mph) a velocity augmentation method has been devised which uses wing-mounted rockets to accelerate the test specimen on its downward swing. Two Falcon rockets are mounted at each engine nacelle location and provide a total thrust of 77,850 N.

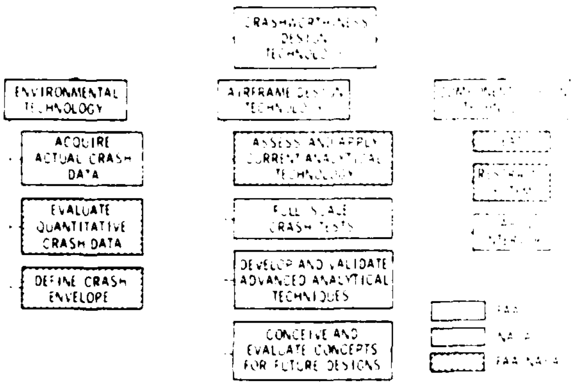


Fig. 1 Agency responsibilities in joint FAA/NASA general aviation crashworthiness program.

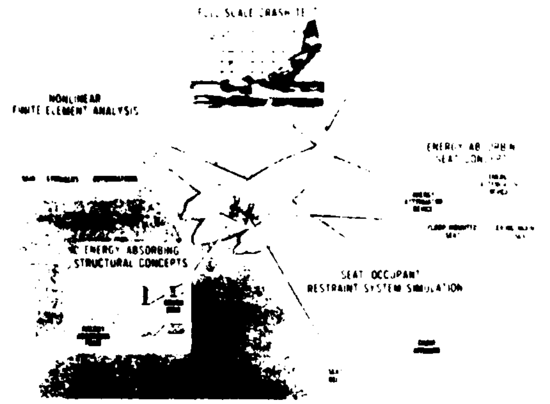


Fig. 2 Research areas in Langley general aviation crash dynamics program.

The aircraft is released after rocket ignition, and the rockets continue to burn during most of the downward acceleration trajectory but are dormant at impact. The velocity augmentation method provides flight path velocities of 26.8-44.7 m/s (60-100 mph) depending upon the number and burn time of the rockets used.

Instrumentation

Data acquisition from full-scale crash tests is accomplished with extensive photographic coverage, both interior and exterior to the aircraft using low-, medium-, and high-speed cameras and with onboard strain gages and accelerometers. The strain gage type accelerometers (range of 250 and 750 g at 0-2000 Hz) are the primary data generating instruments, and are positioned in the fuselage to measure accelerations both in the normal and longitudinal directions to the aircraft axis. Instrumented anthropomorphic dummies (National Highway Traffic Safety Administration Hybrid II) are on board all full-scale aircraft tests conducted at Langley. The location and framing rate of the cameras are discussed in Ref. 1. The restraint system arrangement and type of restraint used vary from test to test.

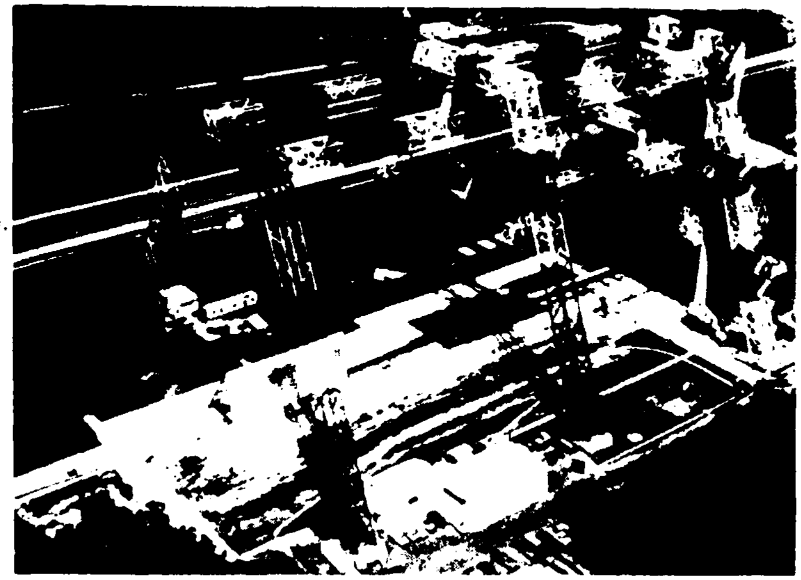
Tests Conducted

A chronological summary of the full-scale crash tests conducted at the Impact Dynamics Research Facility is represented in Fig. 4. The shaded symbols are crash tests that have been conducted, the open symbols are planned crash tests. Different symbols represent different types of aircraft under different impact conditions; for example, o represents a twin-engine specimen impacting at 26.8 m/s (60 mph) while ▵ represents the same twin-engine specimen, using the velocity augmentation method, impacting at 40.2 m/s (90 mph). Various types of aircraft have been successfully crash tested at Langley from 1974 through 1978 including CH-47 helicopters, high and low wing single-engine aircraft, and aircraft fuselage sections. Data from these tests are presented in Refs. 2-6. The aircraft fuselage section tests are vertical drop tests conducted to simulate full-scale aircraft cabin sink rates experienced by twin-engine aircraft tested earlier. The response of the aircraft section, two passenger seats, and two dummies are being simulated analytically (see section on Nonlinear Analysis). Some single-engine crash tests were conducted using a dirt impact surface but most were conducted on a concrete surface. The dirt embankment was 12.2 m (40 ft) wide, 24.4 m (80 ft) long, and 1.2 m (4 ft) in depth. The dirt was packed to the consistency of a ploughed field with a CBR of approximately 4. The variation of full-scale crash test parameters is not complete and does not consider such effects as aircraft overturning, and cartwheeling, fire, or tree and obstacle impact.

Controlled Crash Test and Las Vegas Accident

On Aug. 30, 1978, a twin-engine Navajo Chieftain, carrying a pilot and nine passengers crash landed in the desert

Fig. 3 Langley Impact Dynamics Research Facility.



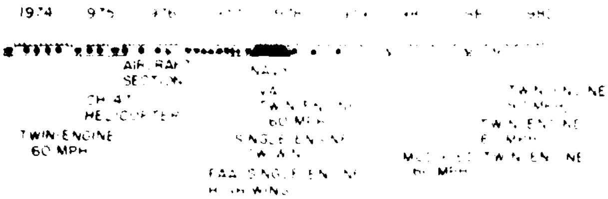


Fig. 4 General aviation crash test schedule.

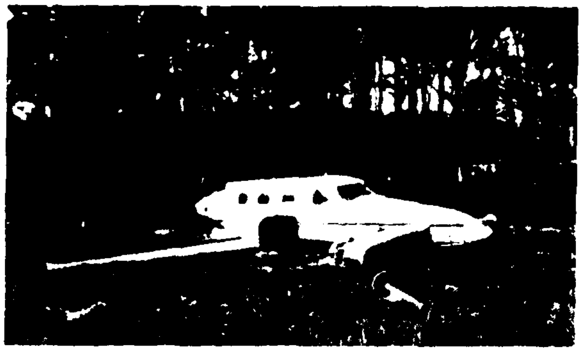


Fig. 5a Controlled crash.

Fig. 5b Las Vegas accident.

shortly after taking off from the North Las Vegas Airport. All 10 persons on board were killed. A comparative study of this Navajo Chieftain crash and a similar NASA controlled crash test was made. The controlled crash test chosen employed the velocity augmentation method wherein the aircraft reachs a flight path velocity of 41.4 m/s (92.5 mph) at impact. The pitch angle was − 12 deg, with a 5 deg left roll and 1 deg yaw. Figure 5 shows photographs of the two aircraft. The NASA specimen is a twin engine pressurized Navajo, which carries six to eight passengers, and although the cabin is shorter in length it is similar in structural configuration to the Chieftain.

Structural damage to the seats and cabin of the Navajo Chieftain and to the seats and cabin of the NASA test specimen are shown for illustrative purposes in Fig. 6. Much more corroborating structural damage is contained in Ref. 7. It is conjectured that the Chieftain contacted the nearly level desert terrain at a location along the lower fuselage on the right side opposite the rear door. An instant later, the rest of the fuselage and the level right wing impacted. The Chieftain's attitude just prior to impact is assumed, therefore, to have the following impact attitude: pitched up slightly, rolled slightly to the right, and yawed to the left. The two aircraft

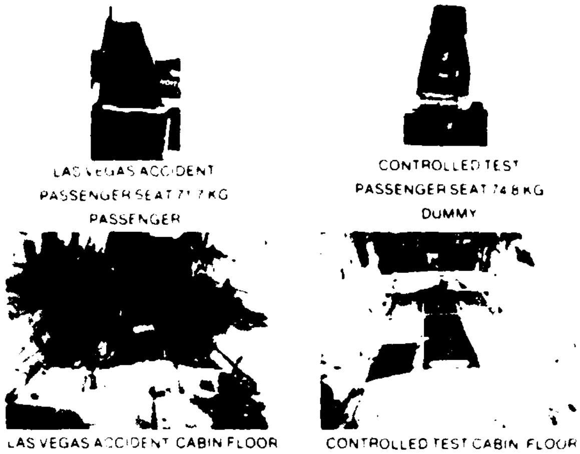


Fig. 6 Damage comparison between controlled test and Las Vegas accident.

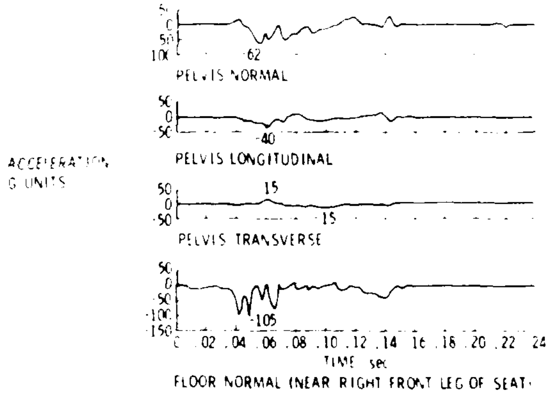


Fig. 7 Acceleration time histories from first passenger and floor of controlled crash test (− 12deg pitch, 41.4 m/s flight path velocity with 5 deg left roll, 1 deg yaw).

differ in roll attitude at impact but are comparable. The structural damage to the cabin of the Chieftain was much greater than that exhibited by the NASA controlled crash test under correspondingly similar impact attitudes. The damage pattern to the standard passenger and crew seats of the Chieftain was similar to that in the NASA tests, but generally exhibited more severe distortion. The damage patterns suggest similar basic failure modes and, in the case of the seat distortion, a flight path impact velocity in excess of 41.4 m/s (92.5 mph) for the Chieftain. Acceleration time histories from the first passenger seat and floor of the controlled NASA crash test are shown in Fig. 7 where the first passenger corresponds to the damaged seat shown in Fig. 6.

Because of the similarity in the damage patterns exhibited by seats 6 and 8 of the Chieftain and the first passenger seat of the NASA controlled test, generalized conclusions can be drawn relative to certain seat accelerations experienced by those passengers in the Chieftain. The peak pelvic accelerations of passengers 6 and 8 in the Chieftain accident were probably in excess of 60 g normal (to aircraft axis), 40 g longitudinal, and 10 g transverse.

Nonlinear Crash Impact Analysis

The objective of the analytical efforts in the crash dynamics program is to develop the capability of predicting nonlinear geometric and material behavior of sheet-stringer aircraft structures subjected to large deformations and to demonstrate this capability by determining the plastic buckling and collapse response of such structures under impulsive loadings. Two specific computer programs are being developed, one focused on modeling concepts applicable to large plastic deformations of realistic aircraft structural components, and the other a versatile seat occupant program to simulate occupant response. These two programs are discussed in the following sections.

Plastic and Large Deflection Analysis of Nonlinear Structures (PLANS)
Description

For several years Langley has been developing a sophisticated structural analysis computer program which includes geometric and material nonlinearities.[8,9] PLANS is a finite element program for the static and dynamic nonlinear analysis of aircraft structures. The PLANS computer program is capable of treating problems which contain bending and membrane stresses, thick and thin axisymmetric bodies, and general three-dimensional bodies. PLANS, rather than being a single comprehensive computer program, represents a collection of special-purpose computer programs or modules, each associated with a distinct physical problem. Using this concept, each module is an independent finite element computer program with its associated element library. All the programs in PLANS employ the "initial strain" concept within an incremental procedure to account for the effect of plasticity and include the capability for cyclic plastic analysis. The solution procedure for treating material nonlinearities (plasticity) alone reduces the nonlinear material analysis to the incremental analysis of an elastic body of identical shape and boundary conditions, but with an additional set of applied "pseudo loads." The advantage of this solution technique is that it does not require modification of the element stiffness matrix at each incremental load step. Combined material and geometric nonlinearities are included in several of the modules and are treated by using the "updated" or convected coordinate approach. The convected coordinate approach, however, requires the reformation of the stiffness matrix during the incremental solution process. After an increment of load has been applied, increments of displacement are calculated and the geometry is updated. In addition to calculating the element stresses, strains, etc., the element stiffness matrices and mechanical load vector are updated because of the geometry changes and the presence of initial stresses. A further essential ingredient of PLANS is the treatment of dynamic nonlinear behavior using the DYCAST module. DYCAST incorporates various time integration procedures, both explicit and implicit, as well as the inertia effects of the structure.

Comparison with Experiment

PLANS is currently being evaluated by comparison with experimental results on simplified structures. In the order of increasing complexity these structures are: an axial compression of a circular cylinder; a tubular structure composed of 12 elements with symmetric cross sections joined at common rigid joints; an angular frame composed of asymmetric angles and bulkheads with nodal eccentricities at the rigid joints; and the same angular frame covered with sheet material. Static and dynamic analyses of these structures loaded into the large deflection plastic collapse regime have been conducted with PLANS and compared with experimental data in Ref. 10 and reported on in Ref. 11. Presently an analytical simulation of a vertical drop test of an aircraft section is being compared with experimental full-scale crash data. Preliminary computer deformation patterns are shown in Fig. 8 using an implicit Newmark-Beta integration algorithm. The use of implicit time integration methods, for this particular nonlinear problem, resulted in more practical time steps than was previously obtained using an explicit Adams Predictor-Corrector algorithm. The results of this study are reported in Ref. 12.

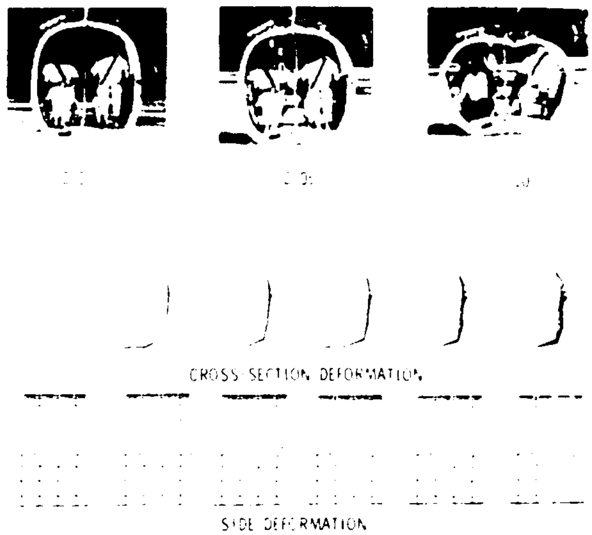


Fig. 8 Computer deformation patterns of an aircraft section impacting rigid surface with vertical velocity of 9.1 m/s (30 ft/s).

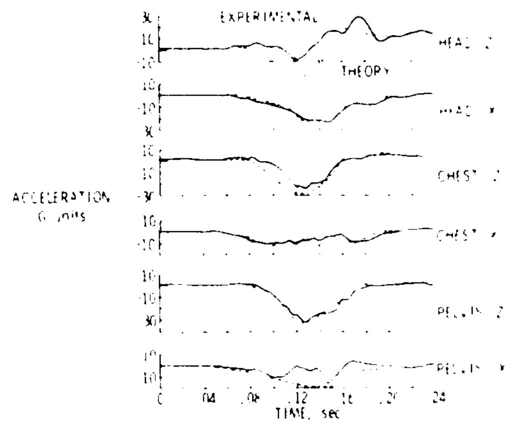


Fig. 9 Experimental and computer dummy accelerations for the −30 deg, 27 m/s full-scale crash test.

Modified Seat Occupant Model for Light Aircraft (MSOMLA)
Description

Considerable effort is being expended in developing a good mathematical simulation of occupant, seat, and restraint system behavior in a crash situation. MSOMLA was developed from a computer program SOMLA funded by the FAA as a tool for use in seat design.[13] SOMLA is a three-dimensional seat, occupant, and restraint program with a finite element seat and an occupant modeled with 12 rigid segments joined together by rotational springs and dampers at the joints. The response of the occupant is described by Lagrange's equations of motion with 29 independent generalized coordinates. The seat model consists of beam and membrane finite elements.

SOMLA was used previously to model a standard seat and dummy occupant in a NASA light aircraft section vertical drop test. During this simulation, problems were experienced with the seat model whenever the yield stress of an element was exceeded. Several attempts to correlate various finite element solutions of the standard seat with OPLANE-MG, DYCAST, and SOMLA, using only beam and membrane elements, to experimental data from static vertical seat loading tests were only partially successful. Consequently, to expedite the analysis of the seat occupant, the finite element seat in SOMLA was removed and replaced with a spring-damper system. Additional modifications to SOMLA added nonrigid occupant contact surfaces (nonlinear springs) and incorporated a three-dimensional computer graphics display. This modified SOMLA is called MSOMLA. A more complete discussion of MSOMLA, its computer input requirements, and additional experimental analytical comparisons can be found in Ref. 14.

Comparison with Experiment

A comparison of full-scale crash test data from the −30 deg, 26.8 m/s (60 mph) crash test and occupant simulation using MSOMLA is presented in Fig. 9. The comparisons between measured and computed acceleration pulses are excellent considering the seat and occupant were subjected to forward, normal, and rotational accelerations. This comparison, using full-scale crash data, demonstrates the versatility of the program's simulation capability.

Crashworthy Seat and Subfloor Structure Concepts

The development of structural concepts to limit the load transmitted to the occupant is another research area in Langley's crashworthiness program. The objective of this research is to attenuate the load transmitted by a structure either by modifying its structural assembly, changing the geometry of its elements, or adding specific load limiting devices to help dissipate the kinetic energy. Recent efforts in this area at Langley have concentrated on the development of crashworthy aircraft seat and subfloor systems.

The concepts of available stroke are paramount in determining the load attenuating capabilities of different design concepts. Shown in Fig. 10 are the three load-attenuating areas which exist between an occupant and the impact surface during vertical descent: the landing gear, the cabin subfloor, and the aircraft seat. Attenuation provided by the landing gear will not be included in this discussion since it is more applicable to helicopter crash attenuators. Using the upward human acceleration tolerance of 25 *g* as established in Ref. 15, a relationship between stroke and vertical descent velocity can be established for a constant stroking device which fully strok[illegible]n less than the maximum time allowable (0.10 s) for hum[illegible] tolerance. This relationshop is illustrated in Fig. 10. Under the condition of a constant 25 *g* deceleration stroke the maximum velocity decrease for the stroking available is 12.2 m/s (40 ft/s) for the seats and 8.2 m/s (27 ft/s) for the subfloor (assuming 30 and 15 cm [12 and 6 in.] in general for a twin-engine light aircraft). For a combination of stroking seat and stroking subfloor, the maximum velocity decrease becomes 15.2 m/s (50 ft/s). These vertical sink rates are comparable to the Army Design Guide recommendations[15] for crashworthy seat design.

Seat

A ceiling-mounted load limiting seat, shown in Fig. 11a, is similar in design to a troop seat designed for Army helicopters[16] and weighs 9 kg (20 lbm). This seat is equipped with two wire bending load limiters which are located inside the seat back and are attached to the cabin ceiling to limit both vertical and forward loads. Two additional load limiters are attached diagonally between the seatpan at the front and the floor at the rear to limit forward loads only. The seatpan in the design remains parallel to the floor while stroking. The length of the stroke is approximately 30 cm (12 in.) in the vertical direction and 18 cm (7 in.) in the forward. The wire bending load limiter is simply a wire element, mounted to pass over a three-wheeled trolley, housed in a tubular casing. In operation, the wire bending trolley, which is attached to the top housing sleeve, translates a wire loop along the axis of the wire during seat stroking at a constant force. This type of load limiter provides a near constant force during stroking, thus making it possible to absorb maximum loads at human tolerance levels over a given stroking distance.

The floor-mounted load limiting seat weighs 10 kg (23 lbm) and employs two wire bending load limiters which are attached diagonally between the seatpan at the top of the rear strut and the bottom of the front legs. While stroking, the rear struts pivot on the floor thus forcing the load limiter housing to slide up inside the seatback (Fig. 11b). The third load limiting concept tested uses a rocker swing stroke to change the attitude of the occupant from an upright seated position to a semi-supine position.

In dynamic tests conducted at CAMI (FAA Civil AeroMedical Institute), the sled or carriage is linearly accelerated along rails to the required velocity and brought to rest by wires stretched across the track in a sequence designed to provide the desired impact loading to the sled. A hybrid II,

Fig. 10 Available stroke for energy dissipation in typical twin engine general aviation aircraft.

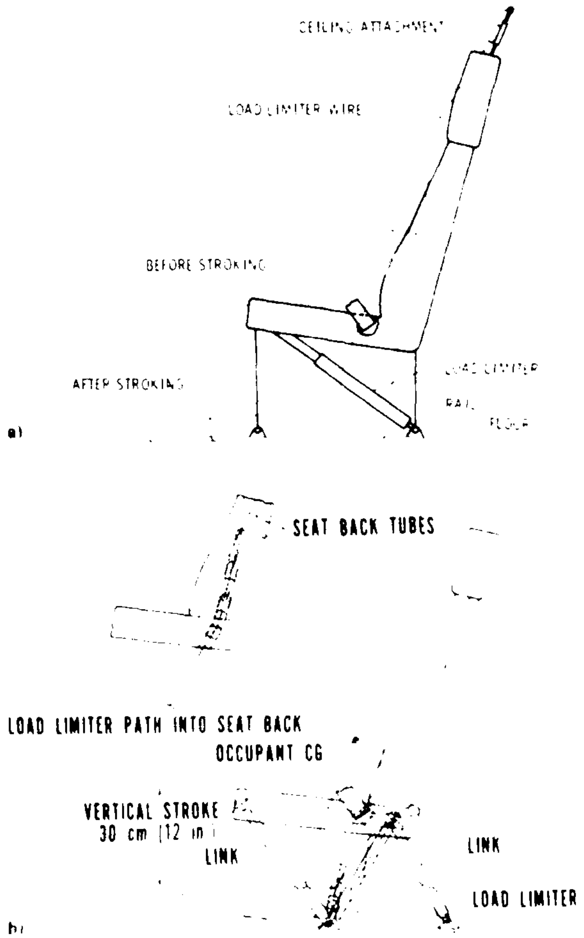


Fig. 11 Passenger seats with wire bending load limiters. a) Ceiling-supported passenger seat; b) Floor-supported passenger seat.

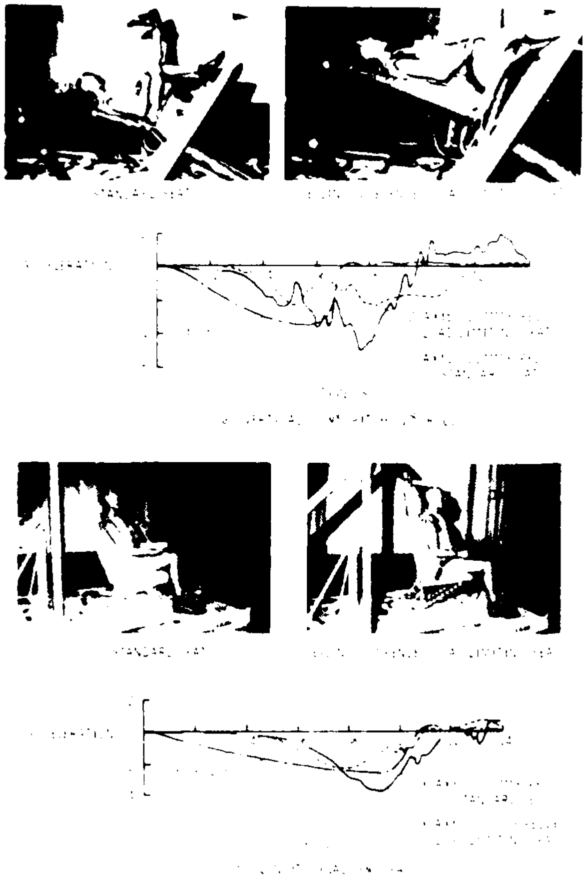


Fig. 12 Pelvis accelerations for dummy in standard and ceiling-mounted (load limiting) seat subjected to "vertical" and "longitudinal" sled pulses.

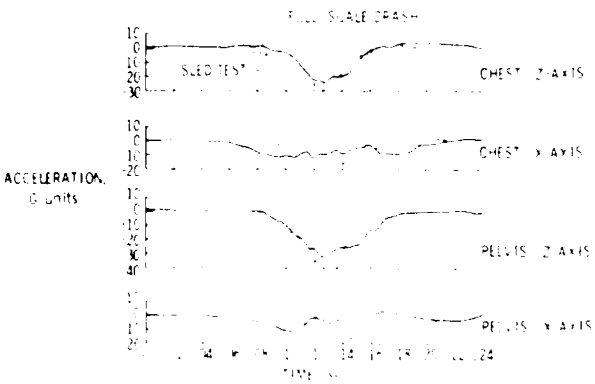


Fig. 13 Dummy accelerations from sled test and from a full-scale crash test under similar impact conditions.

50th percentile dummy instrumented with accelerometers loaded the seats and restraint system on impact. The restraint system for these seats consisted of continuous, one-piece, lap belt and double shoulder harness arrangement.

Time histories of dummy pelvis accelerations recorded during two different impact loadings are presented in Fig. 12 with the dummy installed in a standard seat and in a ceiling-mounted, load limiting seat. The vertical impulse of Fig. 12a positioned the seats (and dummy) to impact at a pitch angle (angle between dummy spine and direction of sled travel) of − 30 deg and a roll angle of 10 deg. In the "longitudinal"

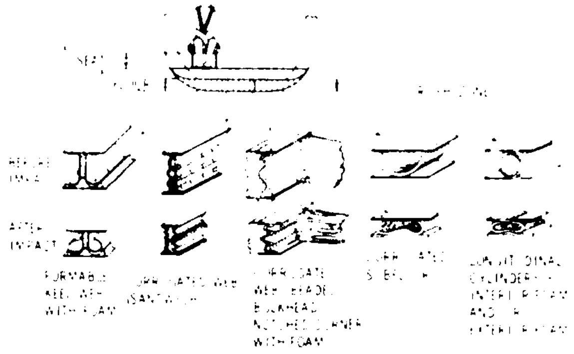


Fig. 14 Load limiting subfloor concepts.

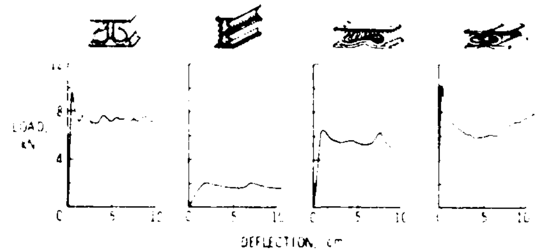


Fig. 15 Load deflection curves for load limiting subfloor concepts.

pulse (Fig. 12b) the seats were yawed 30 deg to the direction of sled travel. The sled pulses are also included in the figure and represent the axial impulse imparted to the inclined dummies. The x- and z-axis of the dummy are local axes perpendicular and parallel to its spine, respectively. The figure shows that for both impact conditions the load limiting seat in general provided a sizable reduction in pelvis acceleration over those recorded during similar impacts using the standard seat.

The impact condition associated with a dummy passenger in one of the full-scale NASA crash tests were quite similar to those defined by the sled test of Fig. 12a, particularly in terms of velocity change, thereby permitting a gross comparison of their relative accelerations. Figure 13 shows that comparison. Although the dummy acceleration traced from the two tests are similar in both magnitude and shape, some phase shift is evident. This agreement suggests that sled testing provides a good approximation of dummy seat response in full-scale aircraft crashes.

Subfloor Structure

The subfloor structure of most [illegible] general aviation aircraft offers about 15-20 [illegible] stroking distance, which suggests the ca[illegible] velocity change of approximately [illegible] (see Fig. 10). Aside from that necessary for [illegible] electrical conducts some volume [illegible] subfloor for energy dissipation through [illegible]. A number of energy absorbing subfloor [illegible] have been advanced and Fig. 14 presents sketches [illegible] candidates. The first three concepts, moving from left to right, would replace existing subfloor structure and allow for: 1) the metal working of floor beam webs filled with energy dissipating foam; 2) the collapsing of precorrugated floor beam webs filled with foam; or 3) the collapsing of precorrugated foam filled webs interlaced with a notched lateral bulkhead. The remaining two concepts eliminate the floor beam entirely and replace it with a precorrugated canoe (the corrugations running circumferentially around the cross-section) with energy dissipating foam exterior to the canoe; and foam-filled Kevlar cylinders supporting the floor loads.

These five promising concepts are being tested both statically and dynamically to determine their load deflection characteristics. Some examples of the static load deflection behavior obtained from four of the five concepts are shown in Fig. 15.

After repeated testing and sizing (geometric optimizing) of these load limiting devices, the three most promising will be chosen for integration into complete subfloor units to be used as the subfloors in aircraft sections. Drop tests of these aircraft sections will then be conducted at velocities up to 15.2 m/s (50 ft/s) to evaluate their performance as compared to unmodified subfloor structure. A static crush test will also be performed on one of each of the subfloor units.

Conclusion

Langley Research Center has initiated a crash safety program that will lead to the development of technology to define and demonstrate new structural concepts for improved crash safety and occupant survivability in general aviation aircraft. This technology will make possible the integration of crashworthy structural design concepts into general aviation design methods and will include airframe, seat, and restraint system concepts that will dissipate energy and properly restrain the occupants within the cabin interior. Current efforts are focused on developing load limiting aircraft components needed for crash load attenuation, in addition to considerations of modified seat and restraint systems as well as structural airframe reconfigurations. The dynamic nonlinear behavior of these components is being analytically evaluated to determine their dynamic response and to verify design modifications and structural crushing efficiency. Seats and restraint systems with incorporated deceleration devices are being studied that will limit the load transmitted to the occupant, remain firmly attached to the cabin floor, and adequately restrain the occupant from impact with the cabin interior. Full-scale mockups of structural components incorporating load limiting devices are being used to evaluate their performance and provide corroboration to the analytical predictive techniques.

In the development of aircraft crash scenarios, a set of crash test parameters are to be determined from both FAA field data and Langley controlled crash test data. The controlled crash test data will included crashes at velocities comparable with the stall velocity of most general aviation aircraft. Close cooperation with other governmental agencies is being maintained to provide inputs for human tolerance criteria concerning the magnitude and duration of deceleration levels and for realistic crash data on survivability. The analytical predictive methods developed herein for crash analyses are to be documented and released through COSMIC.

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2.3 Transport Aircraft

In addition to some discussion of helicopters and general aviation aircraft, the following two papers contain excellent reviews of transport crash response research. These two papers are reproduced in full in the following by the kind permission of the authors.

AIAA-81-0803
Designing for Aircraft Structural Crashworthiness

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AIAA/SAE/ASCE/ATRIF/TRB 1981 International Air Transportation Conference

May 26-28, 1981/Atlantic City, New Jersey

[illegible]

Robert [illegible] | [illegible]
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Hampton, VA [illegible] | Atlant[illegible]

Abstract

This report describes structural [illegible] crash dynamics research activities being [illegible] on general aviation aircraft and transport [illegible] craft. The report includes experimental and analytical correlations of load-limiting sub[illegible] and seat configurations tested dynamically in vertical drop tests and in a horizontal sled deceleration facility. Computer predictions using a finite-element nonlinear computer program, [illegible], of the acceleration time-histories of these innovative seat and subfloor structure are presented. Proposed application of these computer techniques, and the nonlinear lumped mass computer program KRASH, to transport aircraft crash dynamics is discussed. A proposed FAA full-scale crash test of a fully instrumented radio controlled transport airplane is also described.

Introduction

Aviation crash dynamics research has a history (fig. 1) dating back to the pioneering work of Hugh DeHaven in the 1940's. Having survived a midair collision and the ensuing crash that took three lives, DeHaven initiated research into crashworthiness wherein he did onsight investigations of aircraft accidents to identify components and/or subsystems contributing to injuries and/or fatalities. Results from this research produced design guidelines that are still pertinent even today.[1]

The AG-1 cropdusting aircraft, built by Fred Weick at Texas A & M College, incorporated a number of original crashworthiness features based upon the principles espoused by DeHaven.[2,3] These features are still found in today's production agricultural airplanes.

Another milestone in the progress of improved structural crashworthiness of aircraft is the first series of airplane crash/fire tests conducted by the National Advisory Committee for Aeronautics (NACA) Lewis Research Center in 1952. These tests demonstrated some mechanisms which initiate post-crash aircraft fires.[4] In 1964, the Federal Aviation Administration (FAA) conducted two full-scale crash tests of transport airplanes at the Flight Safety Foundation facility, Phoenix, Arizona. One of these tests was using a Douglas DC-7 and the other was using a Lockheed L-1649. These tests were performed with these object[illegible] in mind: (1) to obtain crash environmental data, (2) to study fuel containment, and (3) to collect data on the behavior of various components and equipment aboard the airplane.[5,6] After nearly a twenty-year hiatus, the FAA is proposing another full-scale transport crash test to be conducted in cooperation with the National Aeronautics and Space Administration (NASA). This proposal involves crashing a remotely piloted Boeing B-[illegible] into the [illegible] and [illegible] [illegible] [illegible] [illegible]

[illegible] the late [illegible] the [illegible] Army [illegible] been investigating [illegible] crash injuries and [illegible] crashworthiness research [illegible]. These efforts [illegible] the Army [illegible] Crash Survival Design Guide [illegible] in 1967. The Design Guide [illegible] aircraft engineers and designers [illegible] major milestone toward improved crashworthiness [illegible] military aircraft. By requiring that Army [illegible] be built [illegible] Design Guide requirements, [illegible] crash fires have been virtually eliminated [illegible] overall crashworthiness of the Army aircraft [illegible] has been substantially improved. The Army [illegible] Safety and Helicopter Crash Testing Program (Fig. 1) validated selected crashworthy design concepts.[illegible] The Army's interest in crashworthiness continues to this day. The Design Guide was recently updated on the basis of the latest research results; a crashworthy utility helicopter (Blackhawk) has been put into production, and the production of a crashworthy attack helicopter is imminent.[illegible]

Advanced materials, and in particular graphite-epoxy composites, are being considered by the Army for future helicopter weight-saving designs. The Army has embarked on a program to build an all composite airframe helicopter, but still requiring that the crashworthiness requirements, applicable to metal aircraft, be applied in the design stage.[11]

In 1972, NASA embarked on a cooperative effort with FAA and industry to develop technology for improved crashworthiness in general aviation aircraft. The effort included analytical and experimental structural concept development and involved full-scale crash testing.[12] Prior to 1972, little full-scale crash testing of general aviation airplanes had been done except for some high wing, single engine tests preformed by NASA in 1952, and a crash test program involving two [illegible]C-45J twin-engine airplanes performed by Aviation Safety Engineering and Research (AVSER) in 1964-65 for the U. S. Army.[13,14] The NASA Langley full-scale three-dimensional crash simulations are examining the response of the structure, seats, and anthropomorphic dummies to realistic crash deceleration pulses. Definitive data such as the impact attitude and velocity, crash forces, and dummy accelerations are being obtained in these crash tests that cannot be obtained by investigating field accidents.

The general aviation crash dynamics program is currently being expanded to include commercial transport aircraft. It is recognized that there are significantly fewer transport accidents than either general aviation airplanes or military helicopters. However, in a single transport accident, the lives of several hundred passengers and crew are jeopardized.

The two primary factors contributing to fatalities in transport accidents are trauma resulting from impact forces and fire. The total financial loss for commercial jets between 195[illegible] and 19[illegible] due to accidents is estimated at $1.4 billion. These estimates include hull losses at $63[illegible] million, hull damage at $26[illegible] million, and 2800 liability cases (fatals only) at $52[illegible] million.

The initial effort in this program is focused on a definition of a meaningful research program based in part on a careful study of all transport accident data from 1958-1979. These data have revealed that approximately 80 percent of fatal commercial transport accident occur on or near airports during either approach, landing, or take-off operations. The aircraft during these operations is typically below normal cruise speed and it would appear that potential for survivability could be enhanced through applied crashworthiness technology in the design of the airplane.

General Aviation Crash Dynamics Program

In 1972, the FAA, NASA, and industry embarked on a cooperative effort to develop technology for improved crashworthiness and occupant survivability in general aviation aircraft. The effort included analytical and experimental verification of structural airframe and seat configuration modifications to limit the loads transmitted through the airframe and seat subsystem to the occupant. The methods and concepts developed in the general aviation crash dynamics program will be examined and evaluated to determine their applicability to the transport crash dynamics program. The current research efforts in the general aviation program are expected to make possible future aircraft design concepts having enhanced survivability under specified crash conditions with little or no increase in weight and acceptable cost. A research program intended to accomplish this objective is defined by five technical areas indicated in figure 2. A summary of the pertinent technical accomplishments performed in four of these technical areas - full-scale crash simulation, airframe structural concepts, dynamic analysis methods, and seat/restraint system concepts - are discussed in the following sections (under general aviation crash dynamics). The five technical areas indicated in figure 2 are also applicable to transport crash dynamics including the data base technical area. Under the transport crash dynamics program accident data pertinent to crash dynamics are being examined as a data base to identify fruitful areas of crashworthiness research and to define transport crash scenarios.

Full-Scale Crash Simulation

Full-scale free-flight crash tests were conducted in the Impact Dynamics Research Facility, Langley Research Center in which deceleration histories and structural deformation modes were measured in twenty-four fixed wing and two helicopter crash tests. A comparison was also made between accident field data for a twin-engine airplane and controlled full-scale twin-engine airplane crash test. These test data indicated that the impact loads, as measured in the cabin area in the vicinity of the seats and in the dummy pelvic region were, in most cases, above human tolerance levels even though the livable volume and integrity of the cabin area had been maintained. The need for more uniform and controlled crushing of the subfloor and vertical stroking load attenuation mechanisms for seats became apparent from the full-scale crash simulations.

Airframe Structural Concepts

The cabin floor of a twin-engine aircraft involved in a fatal accident is shown in figure 3. The floor undulations were the result of crushing and overturning moments exerted by the seated occupants as the front legs of the seats applied compressive loads to the floor while, at the same time, the rear legs experienced a tensile loading. The intersections of the longitudinal beams and the lateral bulkheads in the floor provided "hard points" or columns which are very efficient load paths from the underbelly of the airplane to the seat rails.

The airframe structural design philosophy developed under the general aviation program is illustrated in figure 4. The concept is simply to provide an integral stiff upper floor (approximately 5 cm (2 in.)) to maintain structural integrity between the floor and seat and to prevent seat rotation (either transverse or longitudinal) but not allow the floor panels and floor beams to separate. The lower subfloor is designed to provide a uniform crush zone and various structural subfloor concepts have been developed in which the floor beams and lateral bulkheads were modified. One such concept which features corrugated floor beams with notched corners at the intersections of the beams with the lateral bulkheads, is shown in figure 5, along with an unmodified airplane section. These airplane sections are approximately 120 cm (4[illegible] in.) long by 107 cm (42 in.) in width and represent the first passenger row location behind the pilot and the copilot.

Static crush test results are shown in figure 5 for the two subfloor sections. The unmodified subfloor section exhibits much higher (15 kip) crush loads than the modified subfloor (10 kip) and experienced loss of structural integrity between the floor panels and floor beams by buckling of the floor beams (sudden decrease in load) and tearing of the floor panels. The same amount of work (area under the load deflection curve) is involved in the two static crushes but the work is much better controlled in the modified section. Dynamic tests were also conducted on the modified and unmodified sections and a dynamic analysis was performed for comparison with the experimental data. The static crush data of the corrugated beam with notched corners was used as input to the analytical model in the form of nonlinear spring elements representing the corrugated beams. The dynamic test was a vertical drop test onto a concerte surface with an impact velocity of 7.3 m/s (24 fps). The results are presented in figure 6 and show the lower floor accelerations provided by the modified subfloors. The agreement between theory and experimental data (pelvis mass acceleration) for the modified corrugated beam subfloor is excellent.

Dynamic Analysis Methods

An analytical simulation of a vertical drop test of a full aircraft section, shown in figure 7, was used as a vehicle to assess various nonlinear computer programs for crash analysis. The aircraft section, the first passenger row position behind the pilot and copilot, is approximately 120 cm (47 in.) in length and 120 cm (47 in.) in width. This specimen is a complete cabin section in contrast to the subfloor sections discusses in the previous section of this paper. The aircraft section was dropped vertically (and guided by guide posts) to impact symmetrically at 8.5 m/s (28 fps). This vertical impact velocity represents the vertical sink speed measured in a -15° pitch (0°, angle of attack) full-scale crash test at 27 m/s (60 mph). A comparison of fuselage floor outboard vertical accelerations are given in figure 8, for three nonlinear structural analysis computer programs. Two of these programs, ACTION and DYCAST are finite element representations and the program KRASH is a lumped-mass representation of the structure. Details of these computer programs, their capabilities, and developmental assumptions can be found in references 26-29. The results of this comparison indicates a good analytical representation of the first major plastic buckling load by all three programs, however, the DYCAST computer program is seen to follow more closely the second and third peaks both in magnitude and duration. The KRASH computer program, however, is more economical to execute.[6] For these reasons, both DYCAST and KRASH will be further developed and evaluated for use in transport crash dynamics modeling. ACTION will be used as a smaller scale test bed for evaluating new analytical techniques.

Considerable effort has also been expended in developing a good mathematical simulation of occupant, seat, and restraint system behavior during a crash. The FAA-funded computer program SOMLA is a three dimensional seat, occupant, and restraint system program with a finite element seat and an occupant modeled with 12 rigid segments joined together by rotational springs and dampers at the joints.[30] The finite element seat model consists of beam and membrane finite elements capable of modeling rigid body behavior. SOMLA was used previously to model a standard seat and dummy occupant in a NASA light aircraft section vertical drop test. During this simulation, the seat model was replaced with a nonlinear spring damper system. A discussion of SOMLA, its computer input requirements, and additional experimental/analytical comparisons can be found in reference 31. To explore the possibility of incorporating a dynamic finite element seat model in SOMLA, the ceiling supported load-limiting seat and occupant was modeled using DYCAST as shown in figure 9. The occupant model was restricted to two body masses with a CG location in the pelvic region. The seat was modelled using beams, axial rods and nonlinear springs (representing the wire bending energy absorbers (E/A's)). The comparison with the test data in Table I and figure 9 shows excellent agreement. Consequently, the occupant/restraint system model of SOMLA is being integrated with the dynamic finite element DYCAST program for increased versatility.

Seat Restraint System [illegible]

The need for a [illegible] seat [illegible] seat-attached restraint system became apparent [illegible] the assessment of the full-scale [illegible] crash test results. Wire-bending [illegible] seat legs and seat attachment devices [illegible] supported) were developed. [illegible] of prototype seats were conducted at the FAA [illegible] Aero Medical Institute (CAMI) on te [illegible]. The CAMI sled is linearly accelerated along rails to the required velocity and brought to rest [illegible] stretched across the track in a sequence [illegible] to provide the desired impulse loading to the sled. A Hybrid II, 50th percentile dummy instrumented with accelerometers loaded the seat [illegible] restraint system as deceleration of the sled occurs. Figure 9, shows the position of the dummy and seat after such a sled deceleration with the sled pulse showing a maximum deceleration of 34 G and a pulse duration of .06 s. The seat is tilted 30° from the vertical and is yawed [illegible]. The change in velocity is from 12.75 m/s (42 fps) to rest. Note the decrease in acceleration from the 34 G sled pulse to a [illegible] G pelvic acceleration. Floor mounted load-limiting seat designs have provided up to 50% acceleration reductions in similar sled tests. An unmodified (nonstroking seat) configuration however, exhibit dynamic amplification factors as high as 1.5 due to seat rigidity and the motion of the occupant relative to the seat.[32]

Transport Crash Dynamics Program

In 1979, the FAA, NASA, and industry embarked on a cooperative effort to develop technology for improved crashworthiness and occupant survivability in transport aircraft. The effort includes analytical modelling and experimental component and full-scale testing to corroborate structural concept development and to characterize advanced material crashworthiness. The technology developed under the general aviation crash dynamics program discussed earlier in this paper may provide a foundation to advance the crash dynamics technology of transport aircraft, recognizing that transport airplanes have different and unique structural features. These structural features include fuel containment, multi-occupant seat and floor behavior, composite crash response, and multi-occupant egress. The transport crash dynamics technology is expected to make possible future transport aircraft designs having enhanced survivability under specific crash scenarios with little or no increase in weight and acceptable cost.

Accident Data Base

In the first phase of the transport program, it was essential that industry and government examine collectively the accident data base of transport aircraft to identify and define fruitful areas of crashworthiness research (fig. 2, Data Base). Many crashworthiness design features have as their foundation an accident data base identifying the specific aircraft structure and subsystems which contribute to injuries and fatalities. For many years, emphasis in accident investigation was placed on determining the cause of the accident with little or no consideration being given to crashworthiness as relates to injuries and/or fatalities. Within the past fifteen years, the lifesaving and injury-minimizing benefits of

3

crashworthy design were realized within the aviation community and in particular by the U.S. Army. With this realization, design philosophy evolved based on accident data, whereby safety features which would reduce injuries/fatalities in a crash were incorporated early in the aircraft design stages. Having a similar objective, three identical transport accident study contracts were awarded to Boeing Commercial Aircraft Company, Lockheed-California Company and Douglas Aircraft Company, (Long Beach). The specific tasks in these three contracts are summarized as follows:

(a) To review and evaluate transport aircraft accident data, define a range of survivable crash conditions or crash scenarios that may form a basis for developing improved crashworthiness design technology.

(b) To identify structural features and subsystems that influence injuries/fatalities in the crash scenarios defined in (a).

(c) Define areas of research and approaches for improving transport crashworthiness.

(d) Identify test techniques, analytical methods, etc. needed to assess and evaluate the crash response of transport aircraft.

The data base for this study began with a review of the 993 transport accidents which had occurred between the years 1958-1979 and the establishment of a selection process. First disregarded were those accidents in which the structural airframe played no significant role, such as in flight turbulence accidents or maintenance personnel accidents on the ground. Next to be disregarded were the more severe, nonsurvivable midair collision accidents, from the accident data base. In an objective, but somewhat unavoidably subjective manner, a combined total of 241 "survivable" accidents remained to form the data base. The criteria that was generally applied in the selection process included the following conditions: (1) at least 15% of the cabin volume was maintained, (2) the trauma forces were estimated to be within human tolerance levels, and (3) at least one survivor was identified. In a few isolated cases the one survivor condition was waivered when it was felt that trauma forces were within human tolerance levels but a fire hazard existed. The distribution of accident data is illustrated in figure 10. The three transport manufacturers generally examined different accidents, but some accidents were examined by all three manufacturers as indicated in the figure by the cross-hatched area, some by two of the three as indicated by the hatched areas, and other accidents solely by one manufacturer (primarily the accidents involving his aircraft).

Some preliminary survivable accident scenarios are evolving from the studies and are being used in defining classes of accidents. The scenarios consist of four different accident conditions:

(I) A hard landing involving high sink speed with gear collapse, wheels-up airplane attitude, and some swerve. The ranges of forward speed and sink speed are 65 to 82 m/s (126 to 160 knots) and 3 to 10 m/s, respectively. The airplane attitude is symmetrical with 15° pitch, on the runway or within 200 m of the runway.

(II) A collision with an obstacle on the ground (ditch, light poles, vehicles, etc.) with gear down, level airplane attitude, and swerve. The ranges of forward speed and sink speed are 31 to 51 m/s (60 to 100 knots) and 1.5 m/s, respectively. The airplane is in a symmetrical, level, attitude on the runway or within 500 m of the runway.

(III) A severe impact on runway with gear down, high angle of attack and ranges of forward speed and sink speed of 57 to 103 m/s (110 to 200 knots) and 1.5 to 10 m/s, respectively. Airplane attitude, pitch 0°-5°, roll ±5° - ±45°, yaw 0°-10°, on runway.

(IV) A severe ground/water impact off runway with gear up or down, high angle of attack collision, and ranges of forward speed and sink speed of 51 to 103 m/s (100 to 200 knots) and 1.5 to 10 m/s, respectively. Airplane attitude; pitch 0°-45°, roll ±5° - ±45°, yaw 0°-10°, off runway.

The range of impact conditions for these scenarios are tentative and are only given as an illustrative example in this paper. Until such time that all data are finalized, these scenarios and parameter ranges are subject to change.

Fuel Containment

One of the identifiable structural features and subsystems that influence injuries/fatalities in transport accidents is the wing structure fuel tank system. Fuel spillage from a damaged wing structure is one of the primary causes of catastrophic fires and passenger fatalities. The accident studies, previously addressed, clearly identify mechanisms in which wing structure damage could result in fuel spillage; namely, for example, main gear penetration into the fuel tank area, wing-mounted engine pylon failure, or simply failure of the wing structure itself.

Fuel containment is also a research area in which advanced analytical techniques will play a role in analyzing the response of the wing tank to localize crash loadings and studying the main gear and engine pylon failure mechanisms. The nonlinear analytical techniques developed under the general aviation crash dynamics program will be applied to these unique nonlinear transport failure mechanisms. Consideration of advanced composite structural materials and their effect on structural behavior and failure mechanisms must be included in future transport airplane design. The necessary modeling capability for nonlinear dynamic composite structural analysis needs to be developed and verified, first on an element level, and then on more representative aircraft structural component level. Full-scale dynamic testing of instrumented inboard wing tank and fuselage sections subjected to impact (with obstacles) under controlled deceleration and attitude conditions are also anticipated. These full-scale dynamic tests may be conducted at the FAA Technical Center in a newly proposed 68,000 kg (150,000 lb.), 77 m/s (150 knots), catapult facility.

Advanced Analytical Techniques for Transport Aircraft

Airframe and Subsystems. The objective of the analytical efforts in crash dynamics is to develop the capability of predicting non-linear geometric and material behavior of sheet stringer aircraft structures subjected to large deformations and to demonstrate this capability by determining the plastic buckling and collapse response of such structures under impulsive loadings. Two specific computer programs have been developed under the general aviation crash dynamics program and have been discussed previously in this paper. One called, DYCAST, is a finite element program which focuses on modelling concepts applicable to large dynamic deformations of realistic aircraft structures; and the other called KRASH, is a versatile lumped-mass computer program which models the gross behavior of the total aircraft structure. Both of these programs have specific strengths and weaknesses depending on the particular nonlinear problem that is being addressed. Both have been evaluated in the general aviation crash dynamics program, and will be used to model transport aircraft structure.[26]

Occupant/Seat/Restraint System. As mentioned previously, the occupant/restraint system model of SOMLA is being integrated with the dynamic finite element DYCAST program for increased versatility. The new program, called DYSOM, will be used to predict the structural response and occupant behavior of fully or partially loaded multi-occupant transport seats under specific crash loadings.

Both the structural and the occupant-seat programs will be updated to include advanced material modeling to accommodate the newer composite materials anisotropic properties in a macroscopic sense. However, much research work needs to be conducted on post-buckling composite behavior characteristics before an adequate representation of composite failure mechanisms can be predicted.

All of these structural predictive methods will be compared with full-scale and component testing of representative transport structure.

Proposed Full Scale B-720 Transport Crash Test

In order to corroborate analytical predictive methods, test crashworthy structural design concepts, and verify the performance of anti-misting kerosene additives, the FAA will conduct a full-scale transport crash test in 1984. The proposed test specimen, an FAA B-720 four engine jet transport with a 160,000 kg (350,000 lbs) takeoff weight will be crash-tested, by remote control into a designated impact site. The crash scenario will be one selected from the accident data studies. Provisions will be made for the structural failure of the inboard fuel tanks, to take place at maximum approach crash speed, to provide an adequate time period for the testing of the anti-misting kerosene. The cabin interior will be fully instrumented and will contain both standard and crashworthy seat design with fully instrumented anthropomorphic dummies. Crashworthy structural floor features will be assessed during the monitored crash sequence. In addition, pyrotechnic egress device concepts will be evaluated and evacuation slide techniques verified. The B-720 crash test program time chart is given in block form in figure 11. The blocks represent major ongoing activities that are a part of the preparation and assessment exercises associated with the full-scale crash test, scheduled tentatively for the summer of 1984.

A set of objectives associated with three different crashworthy research areas have been identified in the proposed B-720 full-scale crash test plan. These three crashworthy research areas are structural airframe and seat response, anti-misting kerosene performance characteristics, and cabin fire safety materials testing. They are discussed briefly in the following sections.

Structural Airframe and Seat Test. The objectives of the structural airframe and seat tests are as follows: (a) to define dynamic seat pulse data in the form of acceleration time histories at the seat/floor interface, (b) to measure acceleration time-history data throughout the cabin interior for comparison with nonlinear analytical predictions of structural behavior and to determine the level of injury by acceleration indices, (c) to determine accuracy of current flight recorder data, (d) to assess current and improved seat/restraint system/floor behavior, and, (e) to determine structural deformations and failure modes.

Anti-Misting Kerosene. The FAA and NASA are heavily committed to the research and development of an anti-misting fuel additive, which has the potential for precluding the development of the fine mist and associated fireball resulting from fuel spillage. In addition, this additive should exhibit the potential for allowing restoration of the filtration and atomizing characteristics of the fuel, a major requirement for aircraft engine and fuel systems operations.

The proposed B-720 full-scale test utilizing the anti-misting additive will afford the participants an opportunity to: (a) evaluate the performance of the additive's in-flight engine burning characteristics, (b) determine the additive's compatibility with aircraft engines; and, (c) determine flammability and pluming characteristics in a post crash environment.

Cabin Fire Safety. The cabin fire safety area has as its overall objective characterization of aircraft cabin hazards created by external fuel fire especially the contribution of interior materials, and to increase the survivability and safety of occupants in the event of a cabin fire. The proposed B-720 crash test could provide a test bed to evaluate the effectiveness of interior materials as fire retardants when exposed to a fire in a second phase fire test with the airplane at rest.

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Concluding Remarks

The FAA, NASA, and industry have initiated a transport crash dynamics program to develop technology to define and demonstrate new structural concepts that will enhance passenger and crew survivability by minimizing crash force trauma and the potential fire hazard caused by fuel spillage. This technology will facilitate the integration of crashworthy structural design concepts into transport design methods and will consider airframe, seat, floor, fuel tanks and landing gear behavior. In addition, the potential of anti-misting kerosene additives to reduce the fire hazard are to be determined as well as the additives compatibility with aircraft engines.

The dynamic nonlinear behavior of structural components will be determined analytically and verified by full-scale and scaled dynamic tests. The nonlinear analytical techniques developed under the general aviation crash dynamics program will provide a foundation for application to metal transport structure. Consideration of advanced composite structural materials and their affect on structural behavior and failure mechanisms will be studied and design tools developed to aid in future transport airplane design.

In the development of transport crash scenarios, a thorough evaluation of accident data will be made to provide a fundamental understanding of occupant injury mechanisms and aircraft structural response. The effort will be a continuing one, with both industry and government participation and should provide a data base from which design philosophy can evolve. Close cooperation with other governmental agencies is being maintained to provide data on human tolerance limits concerning the magnitude and duration of deceleration levels, toxicity levels, and heat exposure.

To date, the U. S. Army experiences indicate that crashworthy design technology has been a most productive art not only in reducing injuries/fatalities but in achieving these benefits economically. Through continued research and development efforts of government and industry significant gains can be achieved in reducing transport crash hazards by crashworthy design technology.

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Table 1. Ceiling Suspended Seat Comparison

Impact Parameters
Vertical, 12.8 m/s
G_{max} = 34, T = .066s
30° Pitch

	Sled Test	DYCAST Model
Upper E/A Stroke	22.2 cm (8.75 in)	22.9 cm (9.0 in)
Lower E/A Stroke	0.0	0.0
Shoulder Harness (Total)	3251 N (73 lb)	3398 N (764 lb)
Lap Belt	--	5026 N (1130 lb)
Accelerations, Body Axes (G)		
Forward Pelvis	16.0 G	22.0 G
Vertical Pelvis	25.0 G	26.0 G

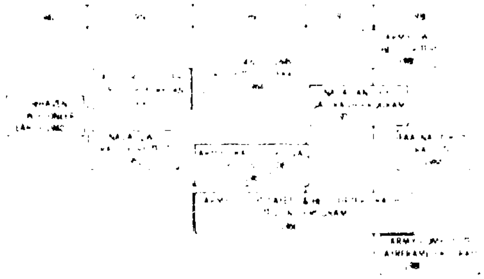

Fig. 1 History of Aircraft Crash Dynamics Program

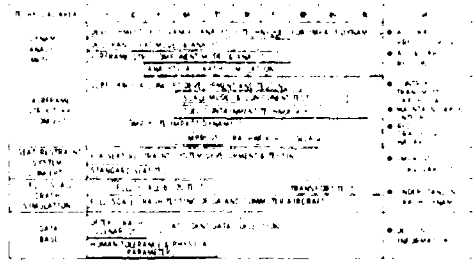

Fig. 2 Aircraft Crash Dynamics Technical Program.

Fig. 3 Cabin floor of crashed airplane.

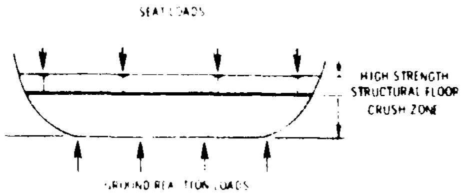

Fig. 4 Lower fuselage design philosophy.

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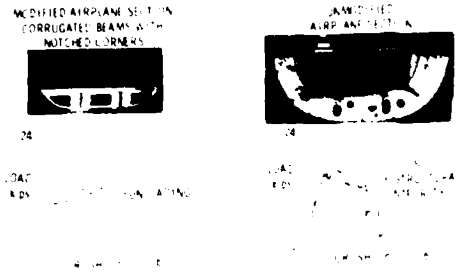

Fig. 5 Static tests of load-limiting subfloor structures.

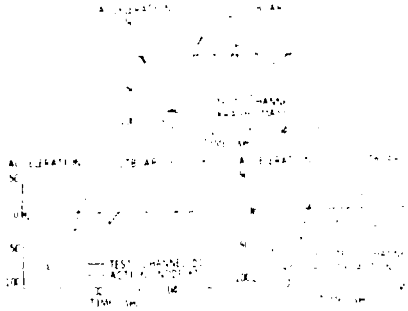

Fig. 8 Comparison of fuselage floor cut-out vertical accelerations

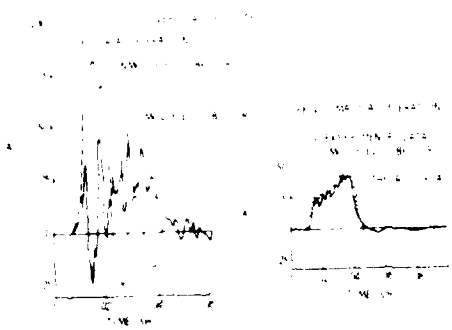

Fig. 6 Dynamic tests and analysis of load-limiting subfloor structures.

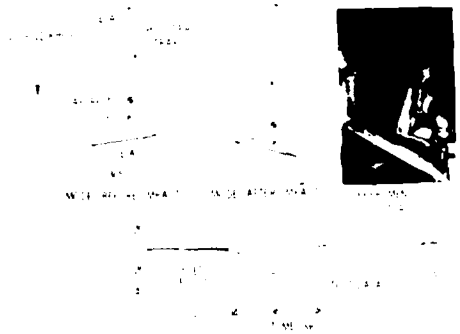

Fig. 9 Analytical & experimental pelvis acceleration in load-limiting seat.

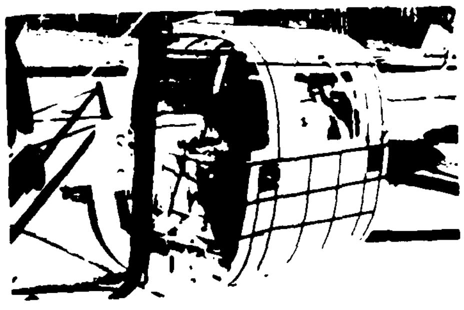

Fig. 7 Fuselage section drop - test specimen.

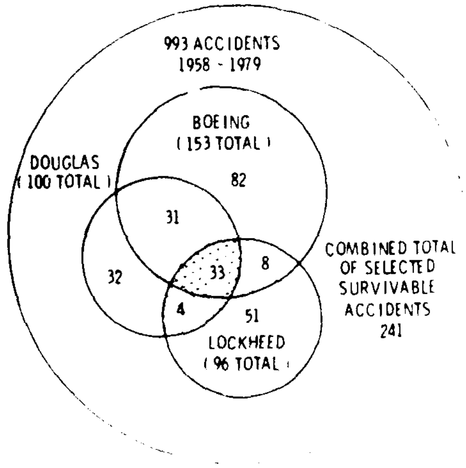

Fig. 10 Selection of transport accidents for study.

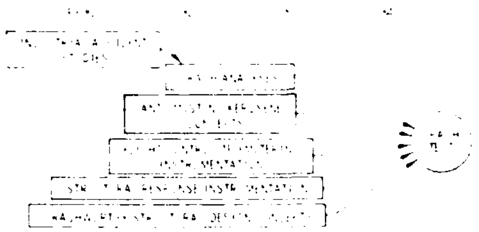

Fig. [illegible] Full-scale B-[illegible] transport crash test schedule

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82-0694

ANALYSIS OF AIRCRAFT DYNAMIC BEHAVIOR IN A CRASH ENVIRONMENT

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Abstract

Differences in the crash environments and design aspects which influence occupant survivability in military and commercial aircraft are discussed. Available analytical techniques for assessing structural behavior during a crash are described. The application of a hybrid technique in assessing aircraft structural behavior and trends in crash environments is provided. Representative mathematical simulations of aircraft crash tests and correlation with light fixed-wing and rotary-wing aircraft test results are shown. The results of a recent FAA NASA sponsored research program involving the review of transport accidents from 1964–79 and the formulation of potential crash scenarios to be considered with future analysis and test verification are presented. Current and future analytical model studies to ascertain the crash dynamics of large transports are also discussed.

INTRODUCTION

In the 1955–1965 era, a popular approach to a determination of aircraft structural crash design capability was to perform full-scale crash tests. Tests of this nature are extremely expensive particularly as the test article increases in size, such as current wide-body jets have. In addition to cost, the test conditions are not repetitive, the results are highly dependent on the impact conditions, and airplane configuration, as well as measurement selection; consequently, essentially only one test parameter data set per test is available. Unfortunately during this time period there was limited correlation with analysis and extrapolation of the test data. However, the 1970s witnessed significant advances in computer modeling of nonlinear crash dynamic behavior, both at the substructure and airframe level. In particular, hybrid (combining analytical and empirical data) and finite element techniques have had the opportunity to be correlated with test data generated for the purpose of verifying and improving the analytical methods. This paper describes differences in the crash environment associated with various categories of aircraft, discusses experimental verification of hybrid analysis with light fixed-wing and rotary-wing aircraft, and describes efforts to develop analytical techniques for transport aircraft.

Crash Environment

The definition of the crash environment is essential before any aircraft crash dynamics capability can be determined. Unfortunately, no single crash environment is applicable to all aircraft. Size, speed, configuration, and operational aspects associated with aircraft influence the crash environment. No universal definition of a crash environment is therefore possible. Descriptions of a survivable crash can include velocity envelopes, crash pulses, crash load factors, and crash scenarios. Comparison of the survivable crash environment and responses of the structures indicates significant differences between small and large aircraft. The survivable large transport accident usually occurs around airports at flight path velocities below 150 knots and vertical descent rates at less than 20 ft sec. These conditions are normally associated with such landing and take-off operations as landing short, overruns, and skidding off the runway. Smaller aircraft, such as helicopters and general aviation airplanes, have lower longitudinal velocities but higher vertical rates of descents during a crash condition; they can include stall spin and emergency landing on unprepared terrain. The percentage of occupiable space in large transports great exceeds that of smaller aircraft. Furthermore, occupants of [illegible] aircraft are much closer to the airframe terrain impact point due to obvious airframe construction differences. The crash pulse experienced by transport occupants varies along the length of the fuselage moreso than do the pulses for the smaller aircraft.

The crash environment for military helicopters, as defined by 95th percentile survivable crash pulses in different directions, was established for U.S. Army helicopters on the basis of [illegible] accidents that occurred between the time period July 1960 and June 1965[1]. In a recent update of the U.S. Army Crash Survival Design Guide[2] the recommended design environment was presented as the design pulse. Although the crash environments are identical to the historical 95th percentile survivable crash pulse, the U.S. Army recognizes that improved crashworthiness increases the severity of the survivable crash, thereby producing a never ending increase in the level of crashworthiness at the expense of aircraft performance. The U.S. Army defines a survival envelope[2] as "the range of impact conditions – including magnitude and direction of pulses and the duration of forces occurring in an aircraft accident – wherein the occupiable area of the aircraft remains substantially intact, both during and following the impact, and the forces transmitted to the occupants do not exceed the limits of human tolerance when current state-of-the-art restraint systems are used." The U.S. Army design pulses are applicable to all aircraft in a given category regardless of weight and operational requirements. Figure 1[2] shows a three-dimensional envelope of combined longitudinal, lateral and vertical velocity (ft sec) changes for helicopters.

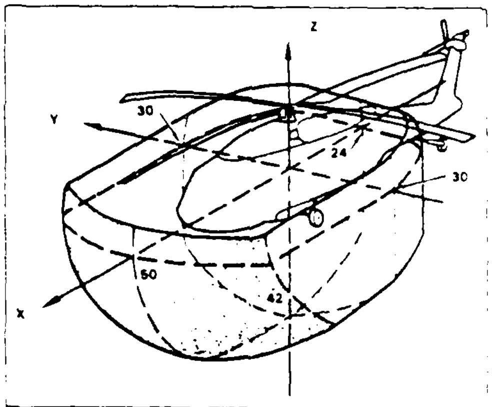

Fig. 1 Three-dimensional display of design velocity change envelope for helicopters

Light fixed-wing (general aviation) aircraft weighing ≤ 12,500 pounds operate at speeds up to 280 knots, carry 1 to 17 people, have one or two engines, and have a low- or high-wing configuration. Aircraft of this type can be involved in stalls, ground collisions, and collisions with obstacles. Accidents[3] have occurred on terrains that are flat (≈ 40%), rolling (≈ 22%), mountainous (≈ 11%), hills (≈ 8%) or dense with trees (≈ 9%) and at airports

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(≈ 2) Figure 2[3] shows the operational velocity weight envelope for current general aviation airplanes. The current emergency landing conditions for airplanes categorized as normal, utility and acrobatic are described in FAR 23.561[4].

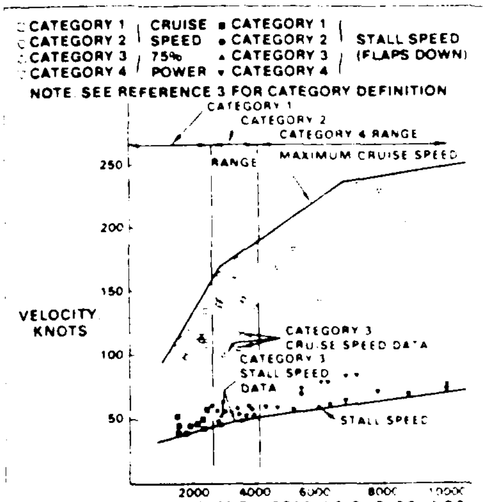


Fig. 2 Operational velocity weight envelope for current general aviation airplanes

The emergency conditions for Transport Category Airplanes, Normal Category Rotorcraft and Transport Category Rotorcraft are provided in FAR 25.561[5], FAR 27.561[6] and FAR 29.561[7], respectively. As is the situation for light aircraft the structure must be designed to give each occupant every reasonable chance of escaping injury in a minor crash landing. Recent in-depth studies[8,9,10] of large transport accidents over the most recent 20 year period revealed that while no accidents are alike in every respect, there are broad similarities for groups of accidents. These similarities allow for a rational arrangement of hundreds of accidents into a few candidate crash scenarios, as is depicted in Table 1. Accidents that are initiated when the aircraft is on the ground and where no unpredictable hazards are involved are rarely fatal. Conversely, when impact occurs at high speed and with a large impact angle, as accidents away from airports often do, the accident has a high probability of fatality. In between the extremes the outcome, in terms of occupant survivability, depends on the surrounding hazards. Figure 3[9] shows the distribution of the severity of accident versus accident type. There are distinct events that can occur during a transport airplane accident. The

Table 1 Identification of candidate crash scenarios

CANDIDATE CRASH SCENARIO	IMPACT CONDITIONS	ACCIDENT TYPE	TERRAIN	HAZARD
GROUND TO GROUND OVERRUN	LOW SINK SPEED LOW FORWARD VELOCITY SYM. A/P ATTITUDE GEARS EXTENDED	TAKEOFF ABORT LANDING OVERRUN	RUNWAY HARD GROUND	DITCH MOUND SLOPE SLAB LIGHT STANCHION
AIR TO GROUND HARD LANDING	HIGH SINK SPEED LANDING VELOCITY SYM. A/P ATTITUDE GEARS EXTENDED	HARD LANDING UNDERSHOOT	RUNWAY HARD GROUND	NONE
AIR TO GROUND IMPACT	HIGH SINK SPEED LANDING VELOCITY UNSYM. A/P ATTITUDE GEARS EXTENDED OR [illegible]	UNCONT. CONTROLLED AND COLLISION STALL UNDERSHOOT	WOODED HILLY	TREES SLOPES RIDGES

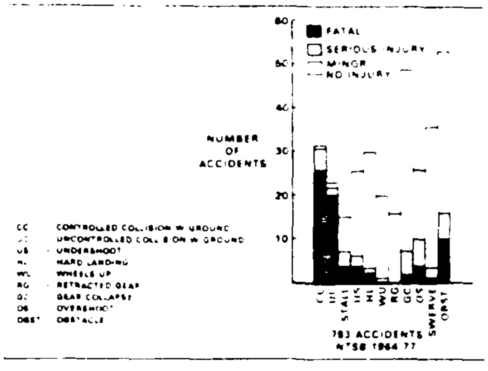


Fig. 3 NTSB accident data injury severity as a function of accident type

occurrence and time sequence of each event and the involvement of structural systems (i.e. fuel tank, seat and attachments, fuselage and wing) is very much related to the particular crash scenario. For each potential crash scenario several failure modes could occur as is illustrated in Figure 4. Each structure related initial failure can lead to additional structure involvement and subsequent failure. The consequence of these events and/or failures are many, including fuel tank line rupture, mass item failure, floor deformation, loss of seat integrity and excessive occupant load. The associated hazards to the occupant are fire (including smoke and inhalation), trauma and evacuation fatalities/injuries.

Airplane Crash Tests

In the 1950–65 time period there were crash tests performed with transport category fixed-wing aircraft which have represented some of the structure related events noted in Figure 4. These tests, which are noted in Table 2, cover a range of airplanes up to 159,000 pounds Gross Take-off Weight and provide some insight into possible trends. The trend would appear to be for the floor responses to decrease in peak magnitude and increase in pulse duration as aircraft mass (size) increases, as is noted in Table 3 and Figure 5. However, this is a fairly general statement since the response can be expected to vary along the length of the fuselage. Figure 6 illustrates this point as well as the sensitivity of the response magnitude to impact angle. Unfortunately for transport airplanes crash test data are limited. The largest airplane crash tested weighed 159,000 pounds, which is substantially lower than many current transport airplanes, particularly the wide-bodied jets. It is unlikely that many larger aircraft will be full-scale crash tested in the near future. Consequently, it is anticipated that analytical methods are a viable alternative to determine crash dynamics characteristics of transport airplanes.

KRASH Experimental Verification

The crash analysis of light fixed-wing[11] and rotary wing[12] aircraft, using program KRASH a hybrid① digital computer program which solves Euler equations of motion for N interconnected masses each with a maximum of six degrees of freedom. The program has met with general acceptance with general aviation and helicopter manufacturers as is attested to by the current large number of KRASH② users. Figure 7[11] shows the post-impact

① A hybrid model allows the user the flexibility to utilize available information, experimental or analytical, in the development of the structure representation.
② Available through the FAA.

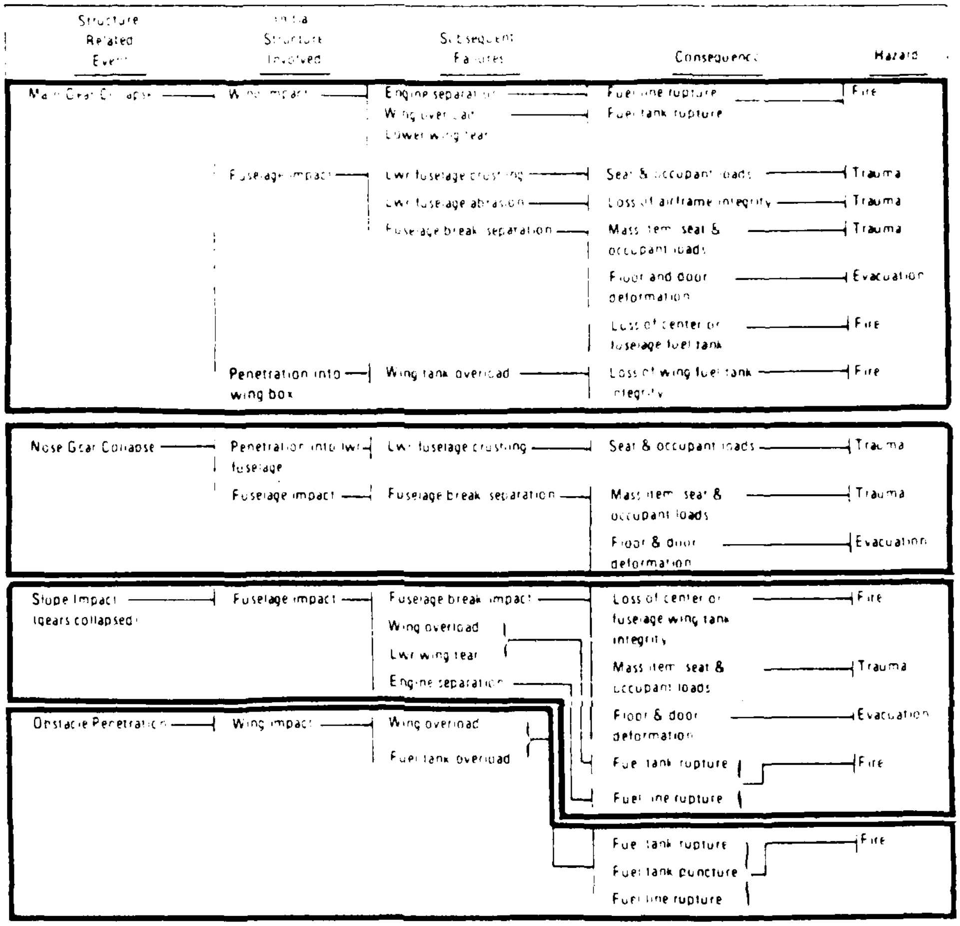


Fig 4 Flow diagram candidate crash scenario

configuration for a combined vertical (23 ft sec) and lateral (18 5 ft sec) full scale crash test of a utility type helicopter Figure 8[12] shows the post-impact configuration for four full-scale crash tests of a single-engine high-wing general aviation aircraft type In both crash test programs high-speed film, accelerometer recorded data and deflection measurements were used to correlate test and analysis results The test conditions for the fixed-wing aircraft are provided in Table 4 The aircraft configurations noted in Figures 7 and 8 were used to help verify program KRASH as an analytical tool for crash dynamics

Table 2 Summary of transport airplane fixed-wing crash test conditions

AIRPLANE	APPROXIMATE WEIGHT kg	(lbs)	VELOCITY m/sec	(ft/sec)	SLOPE (DEGREES)
C-82	19026	(42 000)*	40 8	(133 8)	16
LODESTAR	9739	(21 500)*	39	(127 9)	12
			48 8	(160 2)	16
C-46	18120	(40 000)	41 4	(136 7)	14
			43 5	(142 8)	27
L1649	72027	(159 000)	52 4	(172 0)	6
			33 5	(110 0)	20
DC 7	55266	(122 000)*	67 2	(220 5)	8
			49 3	(161 7)	20

*MAX TAKEOFF WEIGHTS TEST WEIGHT NOT STATED

Table 3 Comparison of peak decelerations and durations

AIRPLANE	LONGITUDINAL DECELERATION g	APPROXIMATE DURATION SEC
FIGHTER FH-1	40	≤ 02
PACKET-TYPE CARGO C-82	15	02
UNPRESSURIZED TRANSPORT, LODESTAR	16	05 08
PRESSURIZED TRANSPORT C-46	9	200

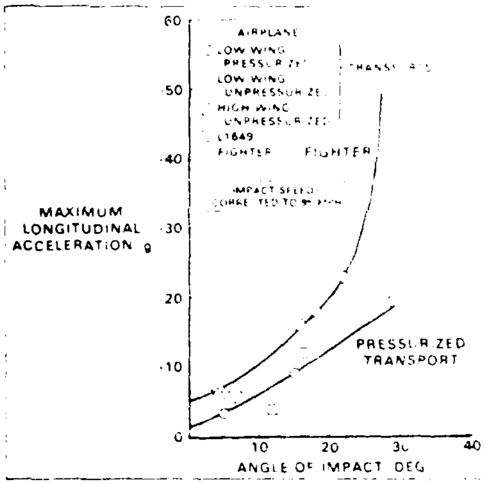


Fig. 5 Effect of airplane configuration and impact angle on maximum longitudinal acceleration

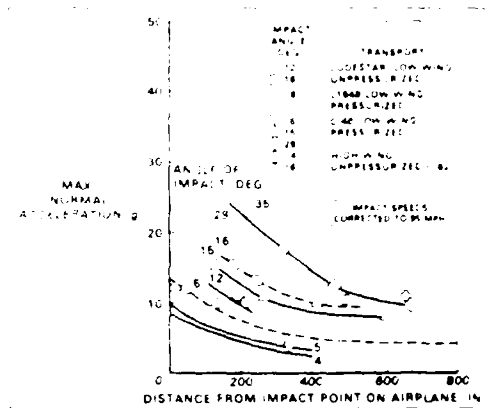


Fig. 6 Effect of position on airplane, airplane configuration and impact angle on maximum normal acceleration

The helicopter math model is shown in Figure [illegible]. The comparison of analysis with the helicopter crash test results are shown in Figure 10. The light fixed-wing airplane math model is shown in Figure 11. Figures 12 and 13 show a comparison [illegible] airplane tests. It is interesting to note that for the [illegible] while the difference in test and analysis peak [illegible] could vary substantially in some instances [illegible] analysis for each of the four impact [illegible] the trend observed in the test data. The significance [illegible] recognized [illegible] Figure 11 was used throughout all four of the airplane tests. Figure 14 shows a comparison of the deformation experienced [illegible] airframe for three of the four fixed-wing airplane tests. There was no significant damage to the airframe in the nose [illegible] (Test 2) and thus the results are omitted from Figure 14. The [illegible] response [illegible] showed [illegible] fixed-wing airplanes indicated that the significant [illegible] experienced during the test was simulated [illegible]

Transport Airplane Crash Modeling

[illegible] crash modeling [illegible] general aviation airplanes [illegible] of transport aircraft for crash dynamics has not yet been [illegible] with experimental data. Current studies [illegible] are being [illegible] available accident data and test data. The [illegible] math models for the light aircraft [illegible] from [illegible] to 48 masses and [illegible] Transport airplanes, because of their size and number [illegible] could easily require an order of magnitude or [illegible] higher number of masses and beams if the same detail were [illegible]. Finite element structural models and occupant representations could easily result in transport airplane models requiring several thousand masses and elements. For example, modeling of

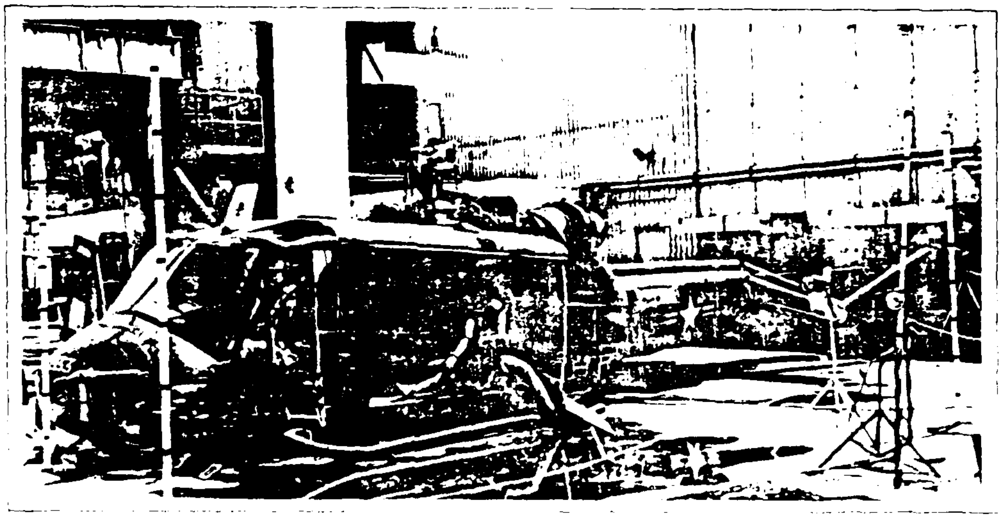


Fig. 8 Post-test damage single-engine high-wing airplanes crash tests

[illegible] airplane substructure [14] utilized almost three times as many Degrees of Freedom (DOF) in the detail finite element model as compared with the more approximate hybrid lumped mass model. In addition, the computer time and cost using the finite element model was also shown to be two orders of magnitude greater than the hybrid method. [illegible] with the conclusion that the hybrid analyst [illegible] were [illegible] to test results. Table 5 [14] indicates various types of analyses and ranges of techniques that could be used for transport airplanes in the future. Part of the rationale for not necessarily having to develop an analytical model in extreme detail is as follows:

- [illegible] of the potential crash conditions (runway, over [illegible] landing gear collapse) the overall vehicle remains intact and, to a first approximation, behaves linearly.
- Nonlinear behavior is restricted to localized areas mostly on the lower extremities of the airplane in direct contact with the ground.
- Since local crushing and nonlinear behavior is not sufficiently widespread throughout the airplane to alter the basic linear behavior of the overall structure, lumped masses (driven at selected discrete locations representative of local crushing behavior) could be used to predict the dynamic response of the overall airplane structure.

For compliance with governing criteria the impact loads acting at the fuselage, landing gear, wing engine attachments must be within their respective structural strengths, otherwise additional

Table 4 Summary of single-engine, high-wing airplane crash test impact conditions

	TEST NUMBER 1	2	3	4
IMPACT VELOCITIES (MPH)				
ALONG FLIGHT PATH	55.5	50.0	60.[illegible]	56.8
LONGITUDINAL	47.4	48.6	47.0	46.4
VERTICAL	28.[illegible]	14.8	33.2	31.9
ANGLES (DEGREES)				
FLIGHT PATH	30.73	[illegible]	34.66	32
IMPACT	30.1[illegible]	13.5	29.4	34.8
ATTACK	6[illegible]	-30.6	4.94	2.8
ROLL	6.3	-3.26	16.76	[illegible]
YAW	3.2[illegible]	[illegible]	7.0	[illegible]
ROTATIONAL VELOCITIES (DEG/SEC)				
PITCH	48.4	6.5	14.3	18.2
ROLL	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
YAW	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE

[illegible] IS NEGATIVE NOSE [illegible]
[illegible] ARE POSITIVE NOSE UP RELATIVE TO GROUND
[illegible] IS POSITIVE NOSE [illegible] RELATIVE TO FLIGHT PATH
[illegible] ARE POSITIVE RIGHT WING DOWN
[illegible] ARE POSITIVE TAIL LEFT AND [illegible]
[illegible]

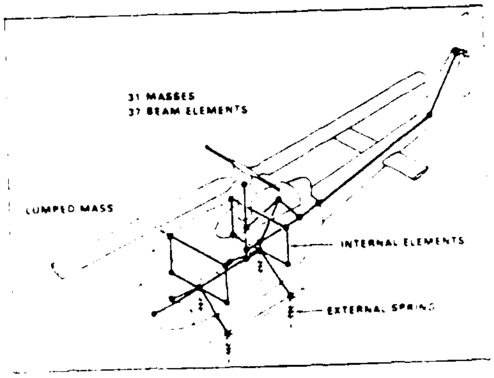


Fig. 9 Helicopter analytical model

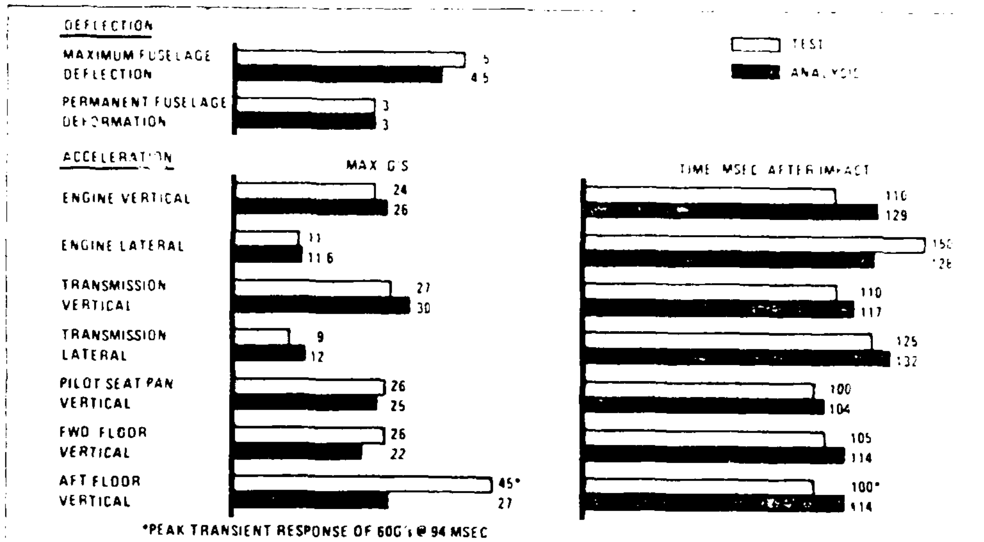


Fig 10 Comparison of helicopter crash test and analysis results

analyses are required. These are key elements and their load-deformation characteristics have to be determined analytically or by means of test.

While, ideally, it would be desirable to model the airframe and occupants in detail, this is probably not practical or necessary for reasons discussed previously. An approach currently being investigated consists of using three analytical models in [illegible] in sequence:

- fuselage airframe
- floor
- seat occupant

Figures 15, 16 and 17 show some representative models of each. The model shown in Figure 15 represents the airframe and to date has not exceeded 44 masses including a [illegible] seat occupant representation at several locations to account for interaction. The primary purpose [illegible]

scenario such as [illegible] from 0.5 to 1.5 sec [illegible] selected fuselage mass stat[illegible] floor model. For a [illegible] tree penetration, this model [illegible] detail for the wing [illegible]

Figure [illegible] depi[illegible] occupant seat [illegible] floor. Mass [illegible] post attac[illegible] posts attach to the floor [illegible] model shown in Figure 16. Masses [illegible] passenger seat. Since [illegible] model [illegible]

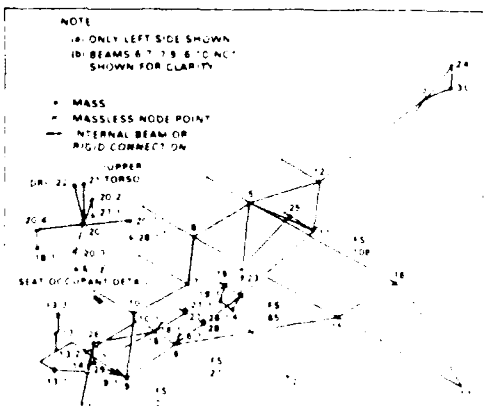
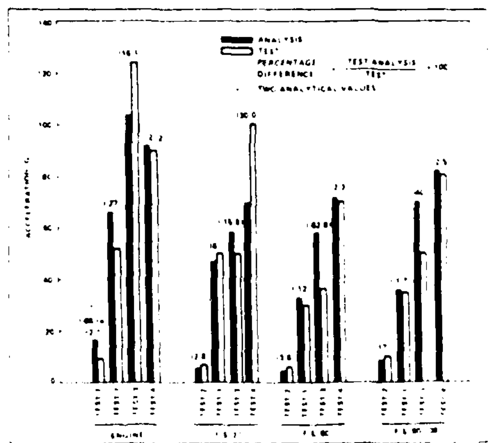


Fig 15 [illegible]



[illegible]

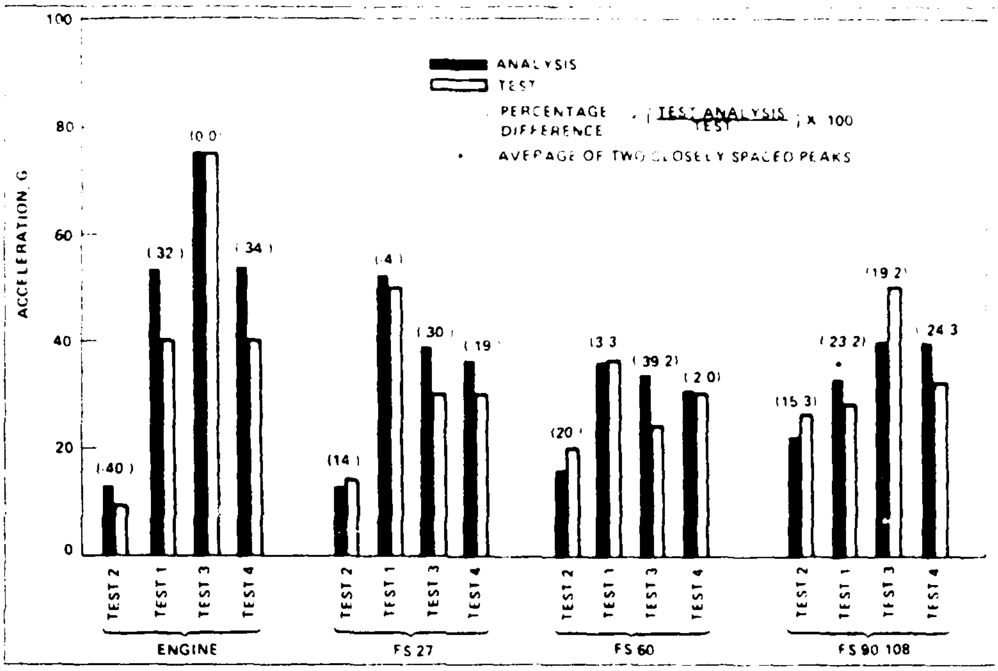


Fig. 13 Single-engine high-wing airplanes analysis and test [illegible]

course, a full model to treat unsymmetrical impact conditions increases the model size and consequently the cost of analysis approximately 60 percent. One can easily visualize that the floor and support structure could vary from aircraft to aircraft and from one section to another. *Figure 18 illustrates some interior arrangement in a 1950s vintage narrow body airplane.* The output desired from the model illustrated in Figure 16 would be the floor pulse as an input to an occupant seat configuration. Since different regions of the fuselage can exhibit their peak response at *different times, the math model representing one portion of the* crash sequence could realistically be run for 100 to 300 milliseconds of simulated crash time.

The airframe model is used to obtain fuselage responses which are subsequently input to a floor model to obtain floor pulses. A

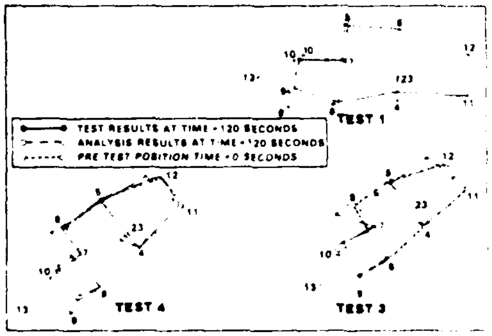


Fig. 14 Single-engine high-wing airplanes analysis and test deformations

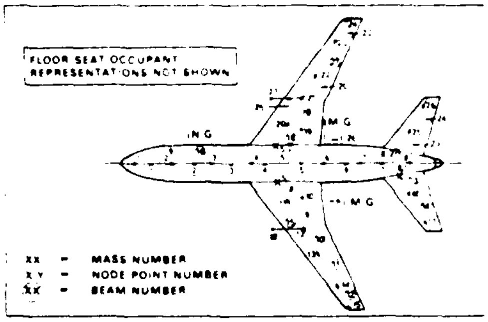


Fig. 15 Transport category airplane airframe analytical model

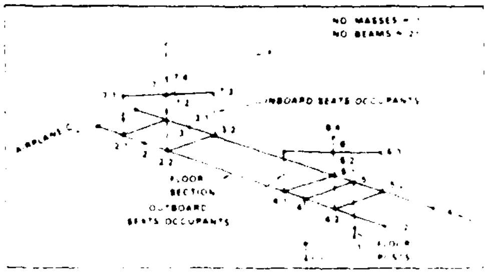


Fig. 16 [illegible] transport floor analytical model

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Table 5 Applicable analytical techniques for related crash dynamic events

APPLICABLE EVENT RESPONSE	ANALYSIS	PROGRAM PROCEDURE	PURPOSE	ADVANTAGE	DISADVANTAGE
• MAIN GEAR COLLAPSE • NOSE GEAR COLLAPSE • WING IMPACT (INITIAL)	LANDING GEAR DETAIL RIGID AIRPLANE CONTOURED TERRAIN (I.E. SLOPE)	• MODAL • HYBRID	• OBTAIN FAILURE MODE OF GEARS • ESTABLISH IMPACT CONDITIONS FOR AIRFRAME AND CRW WING STRUCTURE	• ECONOMICAL TO RUN • MODEL DETAIL WHERE REQUIRED FOR INITIAL EVENT	• INCOMPLETE ANALYSIS INSOFAR AS POST FAILURE BEHAVIOR AND OCCUPANT RESPONSES
• WING GROUND IMPACT • FUSELAGE GROUND IMPACT • OBSTACLE PENETRATION INTO WING • LANDING GEAR PENETRATION INTO WING BOX • NOSE GEAR PENETRATION INTO FUSELAGE	AIRFRAME AND WING REPRESENTATION AND COMPLETE TIME HISTORY OF EVENTS SUBSEQUENT TO GEAR COLLAPSE	• HYBRID	OBTAIN • FAILURES • POST FAILURE BEHAVIOR • AIRFRAME RESPONSES • OCCUPANT RESPONSES	• PERFORM CONTINUOUS ANALYSIS FOR AIRFRAME AND OCCUPANT BEHAVIOR	• COULD LACK DETAIL REPRESENTATION IN SOME AREAS • RELATIVELY COSTLY TO RUN FOR SLIDEOUT CONDITIONS
• ENGINE SEPARATION • SLIDEOUT • OCCUPANT SEAT • OVERHEAD RACK • FUEL TANK	SIMPLE ANALYSIS TO DETERMINE MASS RESPONSES LOSS OF STRUCTURE AND POTENTIAL DOORSILL HEIGHTS AFTER SLIDEOUT	• DYNAMIC RESPONSE CURVE • HYBRID • EMPIRICAL RELATIONSHIP	DETERMINE • DYNAMIC RESPONSE OF MASS ITEMS • DYNAMIC STATIC RELATIONSHIPS • CONSEQUENCE OF LOSS OF STRUCTURE • DOORSILL HEIGHTS FOR EVACUATION	• SIMPLE TO APPLY • REPRESENTS THE BASIC PHENOMENA • CAN BE TRANSLATED INTO TEST REQUIREMENTS	• NOT DETAILED FOR STRESS PURPOSES
• SEAT/RESTRAINT/OCCUPANT	OCCUPANT SEAT RESTRAINT MODEL	• OCCUPANT MODEL	• OBTAIN DETAILS FOR SEAT RESTRAINT SYSTEM AND DELETHALIZATION DESIGN	• UTILIZE PROGRAM SPECIALIZING IN RESTRAINT SYSTEM AND OCCUPANT BEHAVIOR	• NOT REQUIRED IF ONLY BASIC OCCUPANT RESPONSE IS TO BE EVALUATED
• AIRFRAME LOADS • DOOR DISTORTION • FLOOR DISTORTION	AIRFRAME FUSELAGE SHELL DOOR DEFORMATION WING SECTION DETAILS	• FINITE ELEMENT	• PERFORM DETAIL ANALYSIS OF A REGION SECTION	• DETERMINE DETAIL BEHAVIOR WITH STRESS STRAIN RELATIONSHIPS	• COST IS RELATED TO DEGREE OF DETAIL DESIRED

comparison is made with reported data from a previous crash test of a narrow-body aircraft [18]. The range associated with the results are shown in Figures 19 and 20. The trend in the analysis appears consistent with the test data. However, there are differences and their magnitude is dependent on the model's ability to represent the significant phenomena associated with the structure and the ground. The flexibility of the ground for the test was not documented. Additional tests, using the latest techniques in instrumentation and appropriate documentation, with the goal of *enhancing analytical prediction capability*, is desirable.

Figure 17 illustrates a two-passenger seat/occupant arrangement. As in the case of the floor model the excitation would be *an acceleration pulse* at the base such as one would [illegible] a seat dynamic test. In the event a static test were to be simulated *a force time history* would be applied to the simulated occupant mass in the same manner as load is applied to a test body [illegible]. A

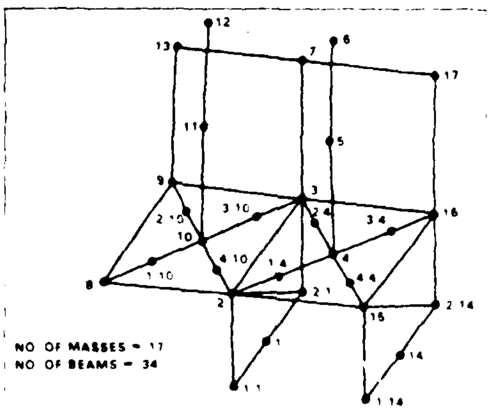

Fig. 17 Two-passenger seat/occupant model

model of this type for dynamic [illegible] run for more than 200 milliseconds crash [illegible] [illegible] double and triple passenger seat models [illegible] listed to assess the response [illegible] particular floor pulse. There are detailed [illegible] [5] which can also be used to assess [illegible] environment. In both the floor and seat [illegible] must be taken to ensure that the boundary [illegible] models are matched.

The concept of model modules to analyze [illegible] scenarios offers some advantages. Table 6 describes [illegible] model sizes, integration time requirements based on KRASH experience and analysis time requirements based [illegible] considerations. From the data shown in Table 6 [illegible] if a detailed floor system were included in the airframe model, the cost would increase substantially for two reasons:

1. The detailed model would have to be run for 1 second even though a fraction of the time is required for [illegible] pulse.

2. The size of the model [illegible] and the total model including a [illegible] representation would [illegible]

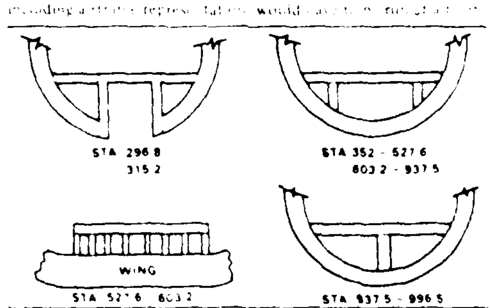

Fig. 18 Lower fuselage [illegible] configurations

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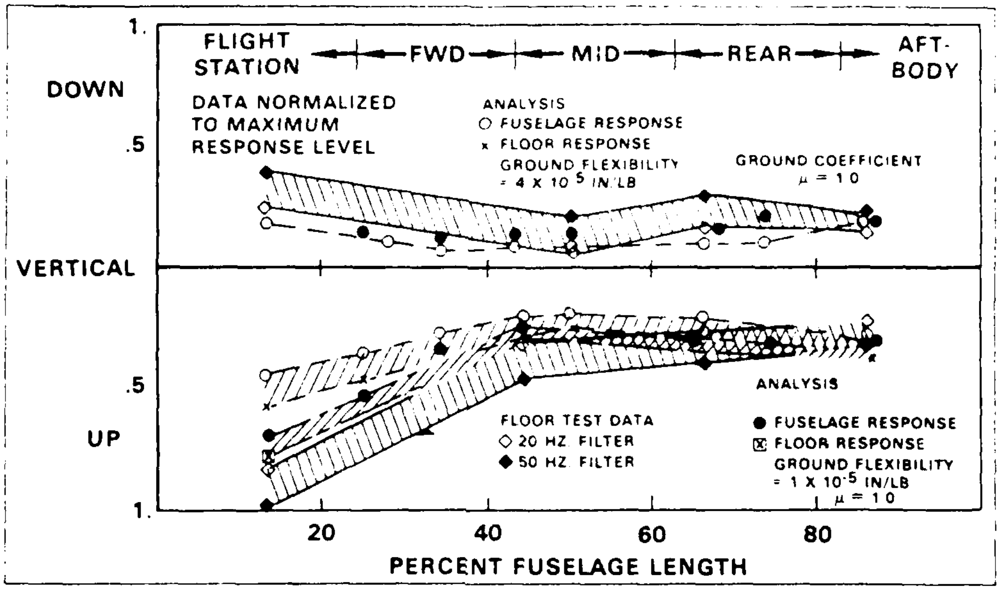

Fig. 19 Vertical acceleration versus fuselage location, slope impact

integration interval as necessitated by the floor model requirements.

In addition, since the hybrid KRASH program has proved valuable in assessing trends a change in one parameter, i.e., occupant weight, would require a total rerun at the maximum time and at a finer integration interval if the airframe, floor and seat occupant models were combined. In the modular approach outlined above, only the last model (seat occupant) need be revised.

Occupant survivability is the ultimate goal in the design for crash considerations. The transport aircraft seating configuration and the range of passengers size and weight vary considerably. For example, *there are two and three seat configurations which* may or may not be fully occupied. Even if occupied, the weights of the individual could vary from 5th percentile females to 95th percentile males. The response and loading of each occupant seating configuration could vary for the same floor pulse excitation.

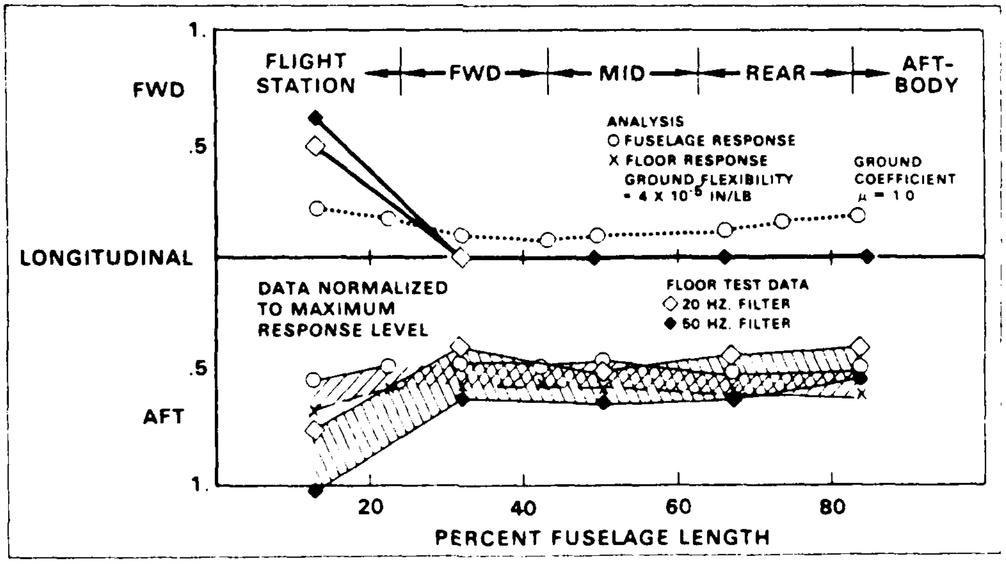

Fig. 20 Longitudinal acceleration versus fuselage location, slope impact

Table 6 Relative models sizes and costs

Symmetrical¹	Airframe Total	Airframe Fuselage	Floor Single Row	Floor Triple Row	Occupant Seat Single	Occupant Seat Double	Occupant Seat Triple
No. Masses	30 43	0 [illegible]	[illegible]	3		[illegible]	[illegible]
No. Beams	35 44	[illegible] 32	31	[illegible]	12	34	26
Integration Interval, Sec	.00C07 .00070		.00004 .00008	.00004 .00008	.0000[illegible] .00004	.00002 .00004	.0000[illegible] .00004
Simulation Time Required, Sec	[illegible]		.100 .300	.08 .300	.100 .200	.100 .200	.100 .200
CPU Sec/MSec Analysis	0.6 [illegible]		.12 .24	.16 [illegible]	0.8 .16	.35 [illegible]	[illegible]
Factor**	30 [illegible]		7 [illegible]	36 [illegible]	80 32	135 54	[illegible] 64

1 - APPLICABLE TO UNSYMMETRICAL MODEL ONLY
* UNSYMMETRICAL MODEL SIZE INCREASE ≈ [illegible] x SYMMETRICAL MODEL
** CPU SEC/MSEC ANALYSES x SIMULATION TIME REQUIRED

Conclusion

Aircraft can differ substantially in size, design, usage, and number of occupants involved, and thus, no one crash environment is applicable to all aircraft. Due to these differences, analytical methods which may be appropriate for one class of aircraft may have to be modified for other aircraft categories. Program KRASH, which is currently being used by helicopter manufacturers to show compliance with U.S. Army crash design requirements, has been correlated with several full-scale light-wing and rotary-wing aircraft crash tests. Despite favorable crash analysis of small aircraft, there is a need to develop improved methods or approaches in the assessment of large transport crash dynamics. The large size of the structure along with the numbers and range of occupants involved and the diverse potential crash scenarios indicate additional refinement in the application of hybrid and finite element techniques. Fortunately, the application of KRASH and DYCAST to the large transport crash environment has been initiated and methodology is being refined under current FAA NASA sponsorship. A full scale crash test of a[20] fully instrumented transport type aircraft is planned which will help to corroborate analytical predictive methods.

ACKNOWLEDGEMENTS

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SECTION 3

RECENT STUDIES OF THE BEHAVIOR OF COMPOSITE MATERIALS AND STRUCTURES UNDER STATIC AND/OR CRASH-IMPACT CONDITIONS

The literature on composite materials and structures has undergone an explosive growth especially in the past 10 years of the past two decades. Very extensive studies on the mechanical, failure, and postfailure behavior of many types of materials, layups, and structural arrangements have been investigated and reported for many types of static, dynamic, impact, and loading situations. Very significant advantages and improvements have been demonstrated by the use of composite materials and structural concepts to replace former all-metallic construction in both secondary and primary structures.

Because of the vastness of the composite materials/structures literature, it is feasible in this review to call attention to only a few of the more recent developments reported in the literature. In particular, attention is called to the following three volumes of recent technical papers [22, 23, and 24, respectively]:

1. Lenoe, E.M., Oplinger, D.W., and Burke, J.J. (Editors), Fibrous Composites in Structural Design, Plenum Press, New York and London, 1980.

2. J.R. Vinson (Editor), Emerging Technologies in Aerospace Structures, ASME, New York 1980.

3. I.H. Marshall (Editor), Composite Structures, Applied Science Publishers, Ltd, Essex, England, and Applied Science Publishers, Inc., Englewood, New Jersey 1981.

In addition, the Journal of Composite Materials has reported many valuable developments in the past 15 years.

In the following subsections, brief reviews of selected papers from these sources are given. These topics include: (a) crashworthiness tests of composite fuselage structure, (b) impact resistance of graphite and hybrid configurations, (c) the effects of elastomeric additives on the mechanical properties of epoxy resin and composite systems, (d) unsymmetrical buckling of thin initially-imperfect orthotropic plates, (e) finite element analysis of instability-related delamination growth, (f) elastic-plastic flexural analysis of laminated composite plates, and (g) behavior and analysis of bolted joints in composite structures. There are, of course, in the literature many papers on each of these topics. Those chosen for this review are considered to be reasonably typical of the current state of the art. Also, the topics selected represent only a small portion of those pertinent to the mechanical behavior and analysis of composite-material structures under loading conditions simulating crash-response conditions.

3.1 A Crashworthiness Test for Composite Fuselage Structure

Foye, Swindlehurst, and Hodges [25] report the results of an experimental investigation of various structural and material concepts seeking to obtain improved crashworthiness for composite fuselage structures. Static failure and postfailure tests were conducted as a [illegible] for future dynamic crash-impact tests to be conducted on promising concepts. Highlights and excerpts of that paper are summarized in the following; all figures and tables are taken directly from Ref. 25.

Composite materials are being considered for application to primary fuselage structure. It is essential that the energy absorption capacity of the composite be as good as that of metallic construction. The complex response of composite structures in the crash environment is difficult to determine analytically and expensive to determine experimentally. In [25] an inexpensive test method is proposed for the quantitative evaluation of different material/structural configurations with regard to their energy absorption capacity.

The test specimens are cylindrical shells 9 inches in diameter and 18 inches long. Some specimens are hat stiffened while others are of honeycomb sandwich construction. The materials used are aluminum, graphite, fiberglass, and Kevlar 49. The cylinders are axially compressed and their load/deflection curves determined. The areas under the curves are the energies dissipated or absorbed during crushing.

The stiffened composite specimens absorbed less energy than the aluminum specimens. Stiffened and sandwich aluminum designs performed comparably. The sandwich composite specimens performed considerably better than the stiffened ones but failed to match the performance of aluminum. It seems that additional energy absorption must be incorporated into the design of composite fuselages to match the performance of comparable aluminum fuselages.

Crashworthiness design has many facets. Among these are fuel containment, seat design, landing gear design, body restraints, flammability, smoke toxicity, flotation equipment, peak deceleration, preservation of occupant space, design criteria, soil scooping, crew escape systems, etc. Present attention is directed only to the capacity of the fuselage structure to crush near the point of impact, thereby dissipating the kinetic energy of the vehicle.

There have been numerous investigations of the various aspects of the energy absorption problem within the scope of structural dynamics, static analysis, structural testing, materials engineering, etc. Each of these investigations is inevitably deficient in some respect. For example, material data alone do not reflect the strengths or shortcomings of the design concept. Analysis methods are of questionable reliability for this class of problem, and full scale testing is very expensive. In [25], however, the authors propose a standard test specimen and large deformation compression test procedure which is simple, economical, and sensitive to materials selection and design concept. It permits the quantitative evaluation of several important material/design configurations of practical importance in fuselage configurations with regard to their ability to absorb or dissipate energy.

The most popular choice of test specimen to simulate the response of helicopter or fixed wing fuselage structures is a circular cylinder or truncated cone. Both are reminiscent of forward fuselage shapes and both are practical test articles. Presently the cylindrical configuration is chosen for testing.

The cylindrical specimens in the current tests were 18 inches long and 9 inches in diameter. The former dimension approximates the typical distance between frames in a cargo helicopter fuselage. The circumference is approximately four times the typical stringer spacing. Three design concepts were tested: internally hot stiffened with solid skin, a similar externally stiffened concept, and an unstiffened honeycomb sandwich design.

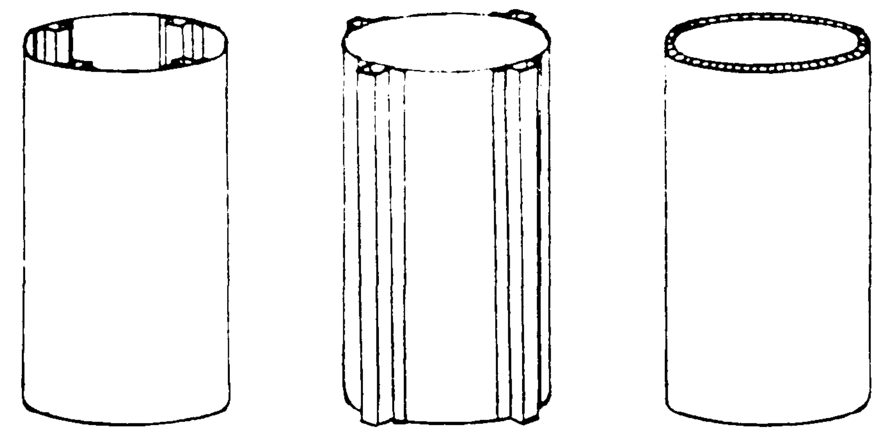


Figure 3.1. Test Specimen Concepts (Ref. 25)

All of the specimens were required to have an ultimate compression strength of at least 20,000 lbs. and an initial torsional stiffness of at least 100,000 lbs. per inch of circumference. The external stringer concept is not practical in fuselage but it does facilitate the observation of stringer behavior.

The longitudinally stiffened cylinders had four hat stiffeners spaced equally (90° intervals) around the circumference while the sandwich specimens all used .25 inch thick aluminum honeycomb core of 6 pcf density. Longitudinal joints in the aluminum specimens were all spaced 90° apart and were located at the stiffeners so that symmetry was maintained. Each test specimen was potted at each end in an epoxy compound to prevent edge splitting and delamination (Fig. 3.2).

At least four different material combinations were used with each of the three design concepts. For each, a metal baseline specimen was constructed from 2024-T3 aluminum. The skin thickness was 0.025" and 0.012" for the stiffened and sandwich specimens respectively, while the aluminum stiffener thickness was 0.032". The stiffened aluminum specimens were riveted together with protruding-head aluminum rivets.

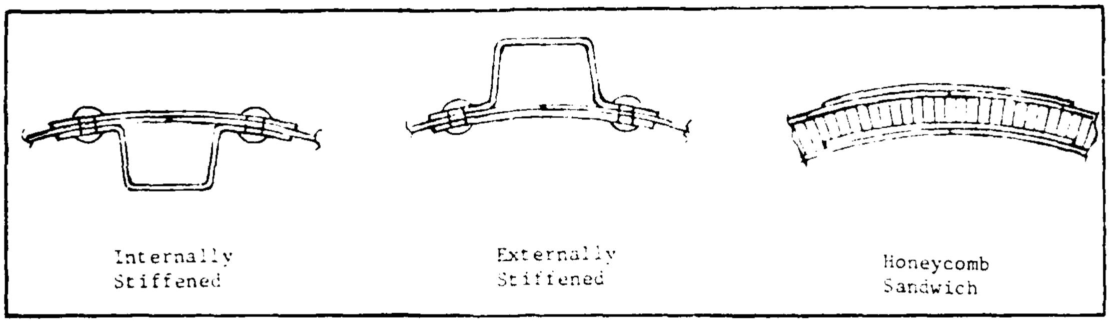


Figure 3.2. Some Stiffener-Joint Concepts (Ref. 25)

The composite specimens of each design configuration used three combinations of materials: all fiberglass/epoxy, all graphite/epoxy, and Kevlar 49 combined with graphite/epoxy. The fiberglass specimens were constructed of Narmco 5208/E7781 woven prepreg with (±45°) skins and (0/90) stiffeners. The graphite specimens used Rigidite 5208/T300 tape. The skins and stringers were (±45) and (0) respectively with Harmco 5208/Kevlar 49 fabric added to the stiffeners to prevent splitting. The graphite/Kevlar 49 specimens used Narmco 5208/Kevlar 49 (45) for the skin panels and Rigidite 5208/T300 tape (0) for the stiffeners. The hybrid sandwich cylinder, the same above mentioned graphite and Kevlar 49 materials were plied together at (0) and (45) respectively. All composite specimens were cocured.

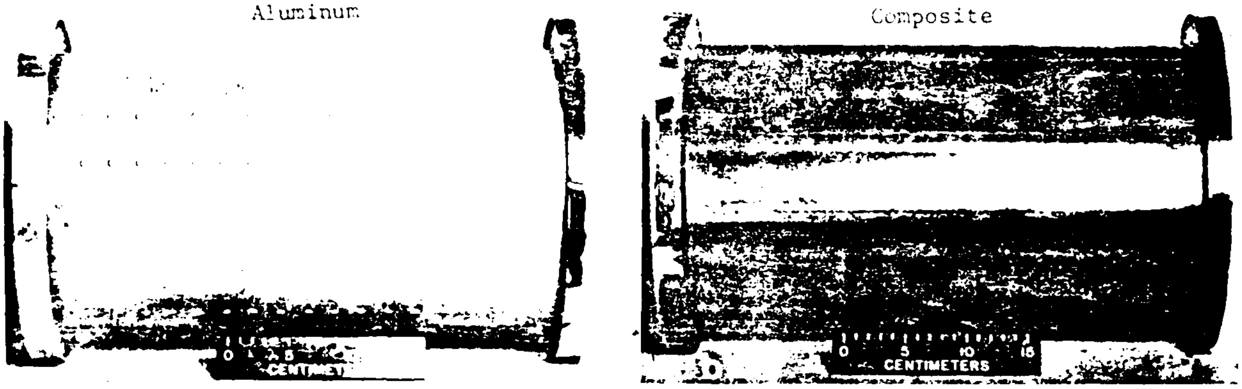


Figure 3.3. Internally Stiffened Specimens (Ref. 25)

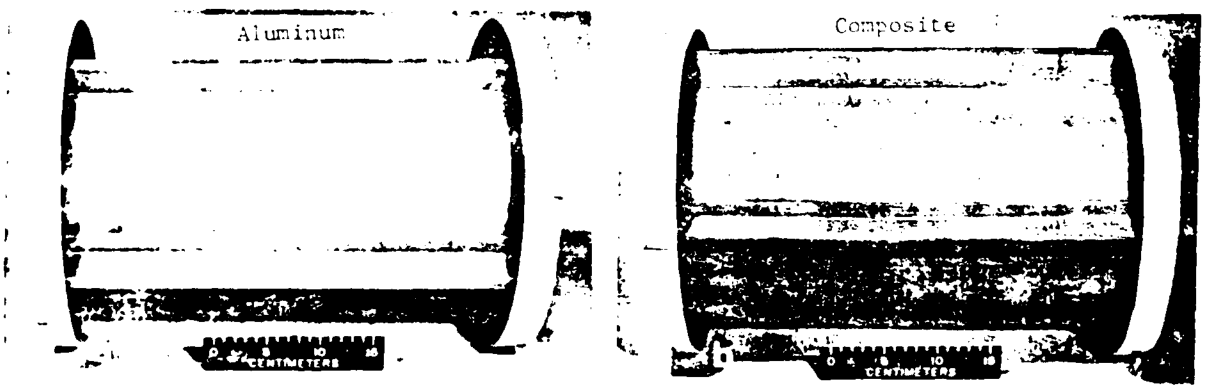


Figure 3.4. Externally Stiffened Specimens (Ref. 25)

Two additional test specimens were constructed which intentionally differed from the specifications given above. One was a Kevlar skin/graphite external stiffener design while the other was a Kevlar skin/aluminum external stringer design. The following table contains a summary of the material/design combinations of each test specimen.

TEST SPECIMEN LIST

SPEC. NO.	TYPE	SKIN MATL.	SKIN THICK. (IN)	STIFFENER MATL.	STIFFENER THICK. (IN)	CORE MATL.	JOINT CONCEPT	FIBER ORIEN.	
								SKIN	STIF.
IA	IS	AL	0.025	AL	0.032		R		
IB	IS	FG	0.050	FG	0.060		B	±45	0/90
IC	IS	FG	0.050	FG	0.060		B	±45	0/90
ID	IS	GR	0.032	GR/K49	0.070		B	±45	0/±45
IE	IS	GR	0.032	GR/K49	0.070		B	±45	0/±45
IF	IS	K49	0.050	GR/K49	0.070		B	±45	0/±45
IG	IS	K49	0.050	GR/K49	0.070		B	±45	0/±45
IIA	ES	AL	0.025	AL	0.032		R		
IIB	ES	FG	0.050	FG	0.060		B	±45	0/90
IIC	ES	GR	0.032	GR/K49	0.070		B	±45	0/±45
IID	ES	K49	0.050	GR/K49	0.070		B	±45	0/±45
IIE	ES	K49	0.050	GR/K49	0.070		B&R	±45	0/±45
IIF	ES	K49	0.050	AL	0.032		B&R	±45	
IIIA	HS	AL	0.012			AL	R		
IIIB	HS	FG	0.060			AL	B	0/90	
IIIC	HS	GR	0.048			AL	B	0/±45	
IIID	HS	K49&GR	0.060			AL	B	0/±45	

IS - Internal Stringer B - Bonded FG - Fiberglass/Epoxy
ES - External Stringer R - Riveted GR - Graphite/Epoxy
HS - Honeycomb Sandwich AL - Aluminum 2024-T3 K49 - Kevlar 49/Epoxy

The test procedure involved placing one of the cylindrical specimens between the heads of a hydraulic testing machine and slowly compressing it axially until it was approximately one-half its original length. An initial 1000 lb. load was applied to securely seat the specimen to the heads. The total axial load was measured with a load cell and the output continually plotted against head motion on an X-Y recorder.

Typical specimens were loaded to ultimate strength at roughly 0.04 inches/minute of head motion, and at 1 inch/min. beyond ultimate load. Within this range of testing rates the residual load carrying capacities of the specimens were insensitive to changes in rate. These rates are several orders of magnitude slower than those experienced in crashes, however.

A typical plot of compression load vs. relative head motion is given in Fig. 3.5. Buckling of the skin was always evident prior to the attainment of peak load for the stiffened cylinders but not for the sandwich cylinders. When ultimate load was reached, there was a sharp and pronounced decrease in the load level. The failed cylinders invariably continued to support load in a spurious manner as fractures progressed. Despite the load irregularities in this region, an average post-ultimate load carrying capability could easily be discerned. This load level began to increase only when one or more of the broken stiffeners made contact with the end epoxy potting compound and began to support load again.

With the observation that a localized volume of material undergoes the primary fracture and deformation it may be surmised that the energy absorption

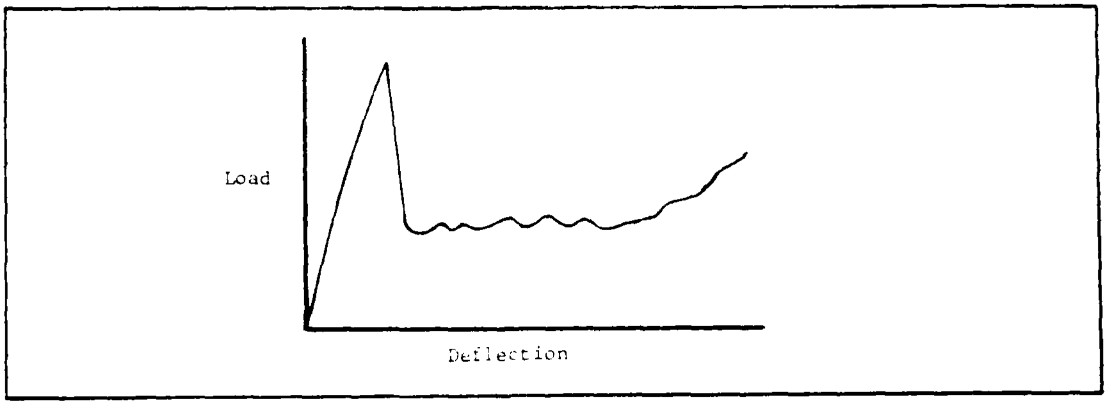


Figure 3.5. Typical Load-Deflection Curve (Ref. 25)

rate is independent of specimen length but is approximately proportional to the circumferential distance around the specimen. This measure of performance cannot be separated from cylinder design details, however. Thus, the energy absorption rate is not a pure property of the material/design configuration alone.

Results for Stiffened Cylinders

Each of the four basic material configurations (aluminum, fiberglass, graphite, and Kevlar/graphite) behaved similarly up to their ultimate strength levels. At approximately one-half ultimate strength, each cylinder began to show evidence of skin buckling near the epoxy ends and between the stringers. This initial pattern developed into a diamond pattern between the stiffeners as the load increased. The slope of the load/deflection curve decreased with increased buckling. In several tests, an audible noise and altered external appearance indicated that one of the stringers had buckled or failed or delaminated from the skin. This was immediately followed by the remaining stringers failing in rapid succession and the load reduced to a fraction of its peak value. Increasing the average compression strain beyond this point had different effects on different materials. The aluminum cylinder creased at the flexure lines of the buckling pattern. The bent stiffeners ripped the skin and the skin tore itself at the crease intersections (Figs. 3.6, 3.7). Progressive local crippling of the stringers and rolling of portions of the hot sections are apparent. The peak load level of the aluminum specimen was 27,750 lbs. (Fig. 3.9).

The fiberglass cylinder reached a peak load of 36,850 lbs. before the skin fractured around the circumference in a jagged pattern. Interference between the stringers and skin caused a cutting action at various points and resulted in large pieces of the skin petalling and breaking off (Fig. 3.8). Compared to the aluminum cylinder, the post-ultimate load capacity was much lower. Parts of the stiffeners remained intact with some completely detached from the skin.

The ultimate load for the graphite specimen was 24,340 lbs. The salient post-ultimate feature of this test was local circumferential cracking of the skin. There was extensive separation of the stiffeners from the skin accompanied by longitudinal stiffener splitting. The graphite cylinders had the lowest post-ultimate load capacity of all the specimens tested.

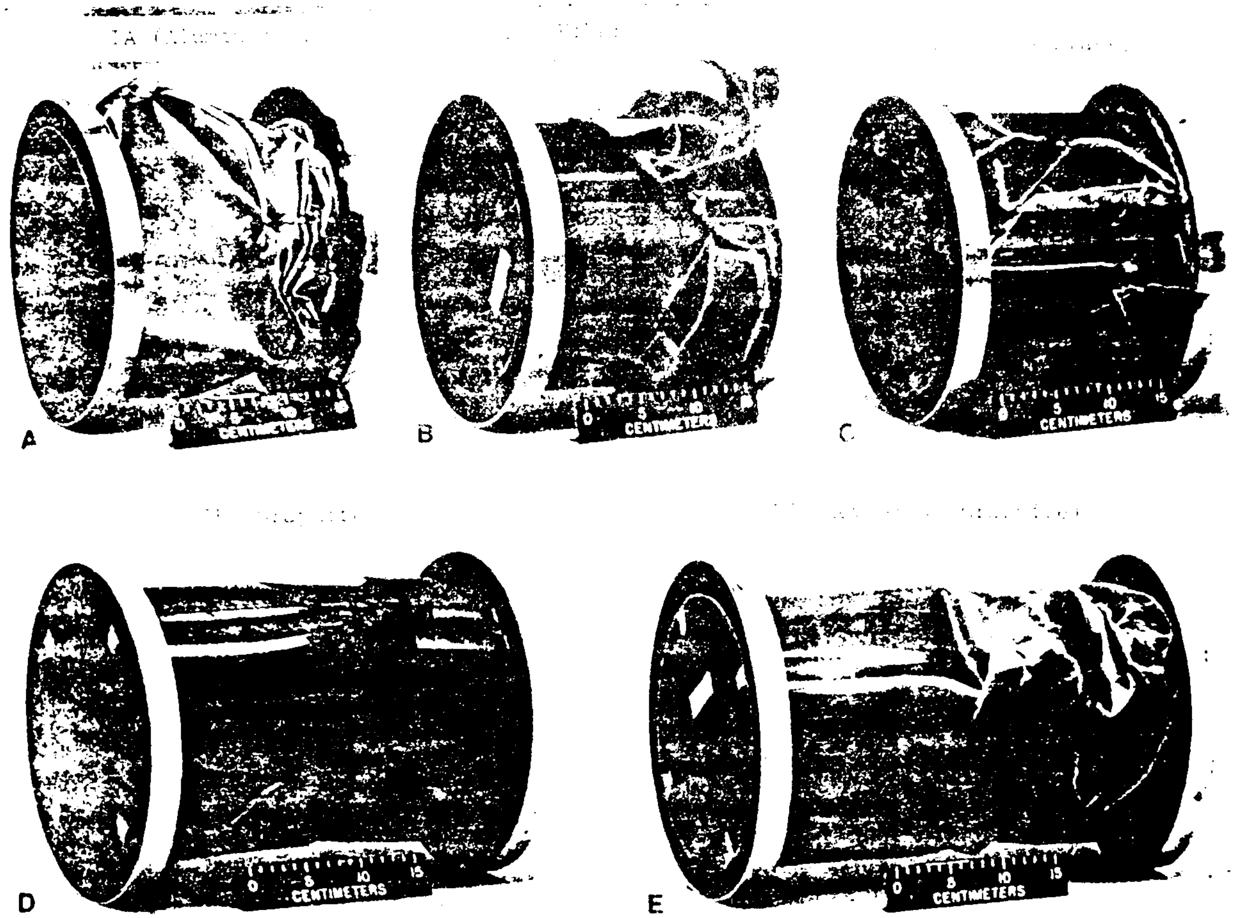


Figure 3.[illegible]. Internally-Stiffened Specimens after Failure [illegible]

The noteworthy features of the tests performed on hybrid Kevlar and graphite stiffener specimens were the absence of skin tearing and rebounding following removal of the load. The interior view (Fig. [illegible]) showed considerable splitting and separation of the stiffeners. The load capacity was only slightly superior to that of the all-graphite specimen.

Results for Sandwich [illegible]

Cylindrical [illegible] cylinders were [illegible] basic material configuration. [illegible] attainment [illegible] their [illegible] specimen [illegible] all [illegible] energy [illegible].

[illegible]

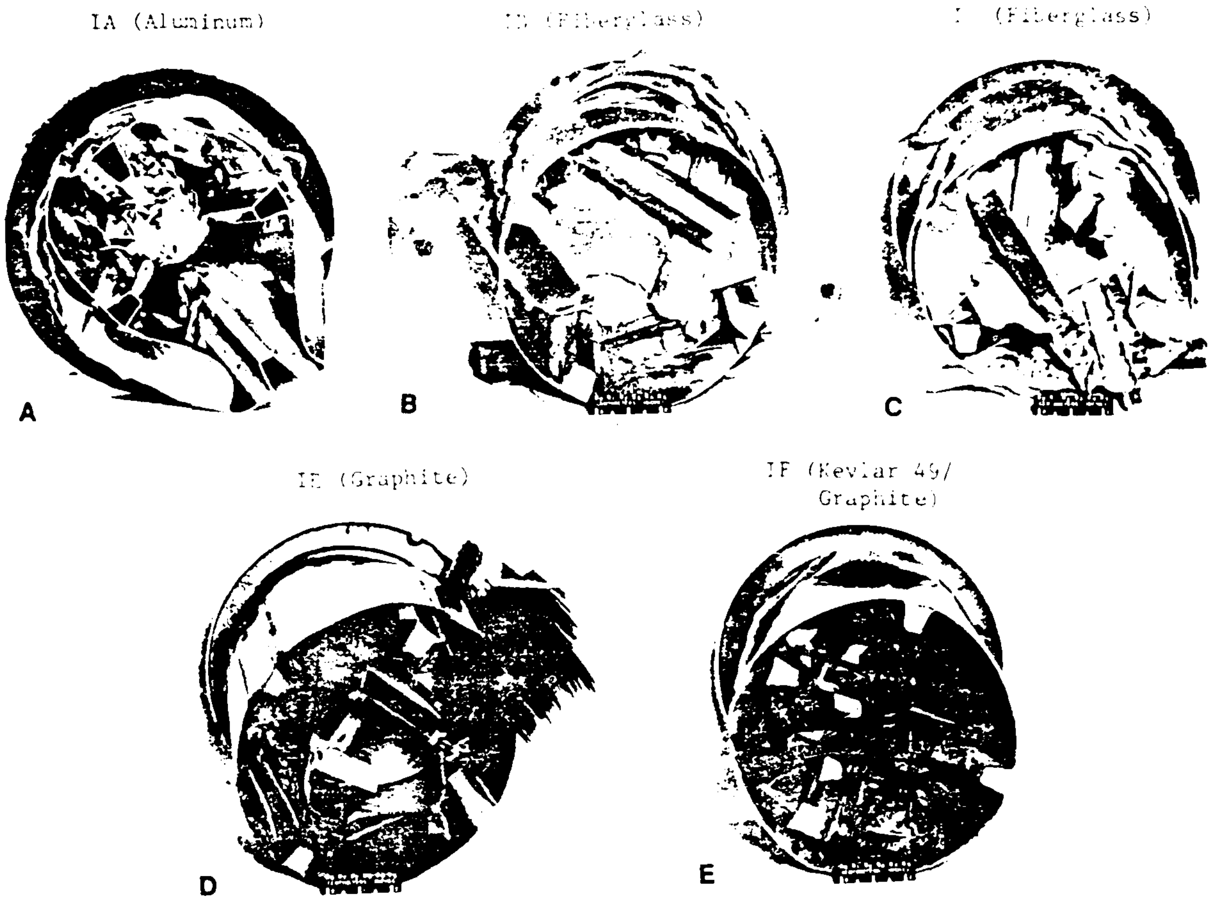


Figure 3.7. Inside View of Internally Stiffened Specimens
After Failure (Ref. 25)

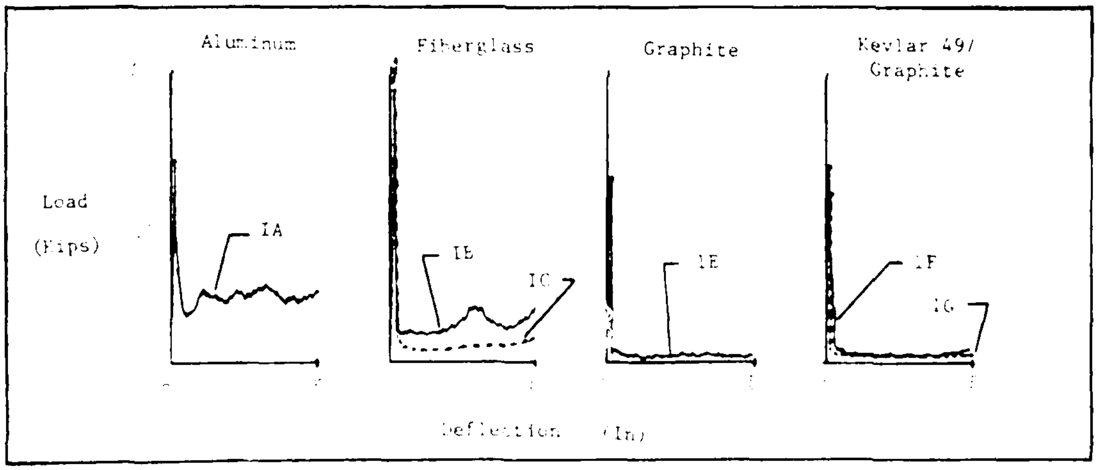


Figure 3.8. Load/Deflection Curves for Internally Stiffened
Specimens (Ref. 25)

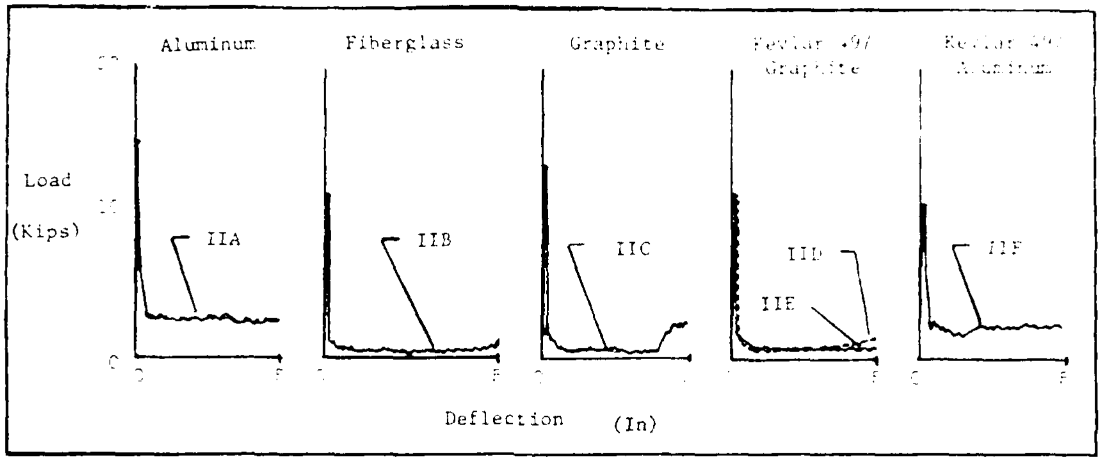


Figure 3.9. Load/Deflection Curves for Externally Stiffened Specimens (Ref. 25)

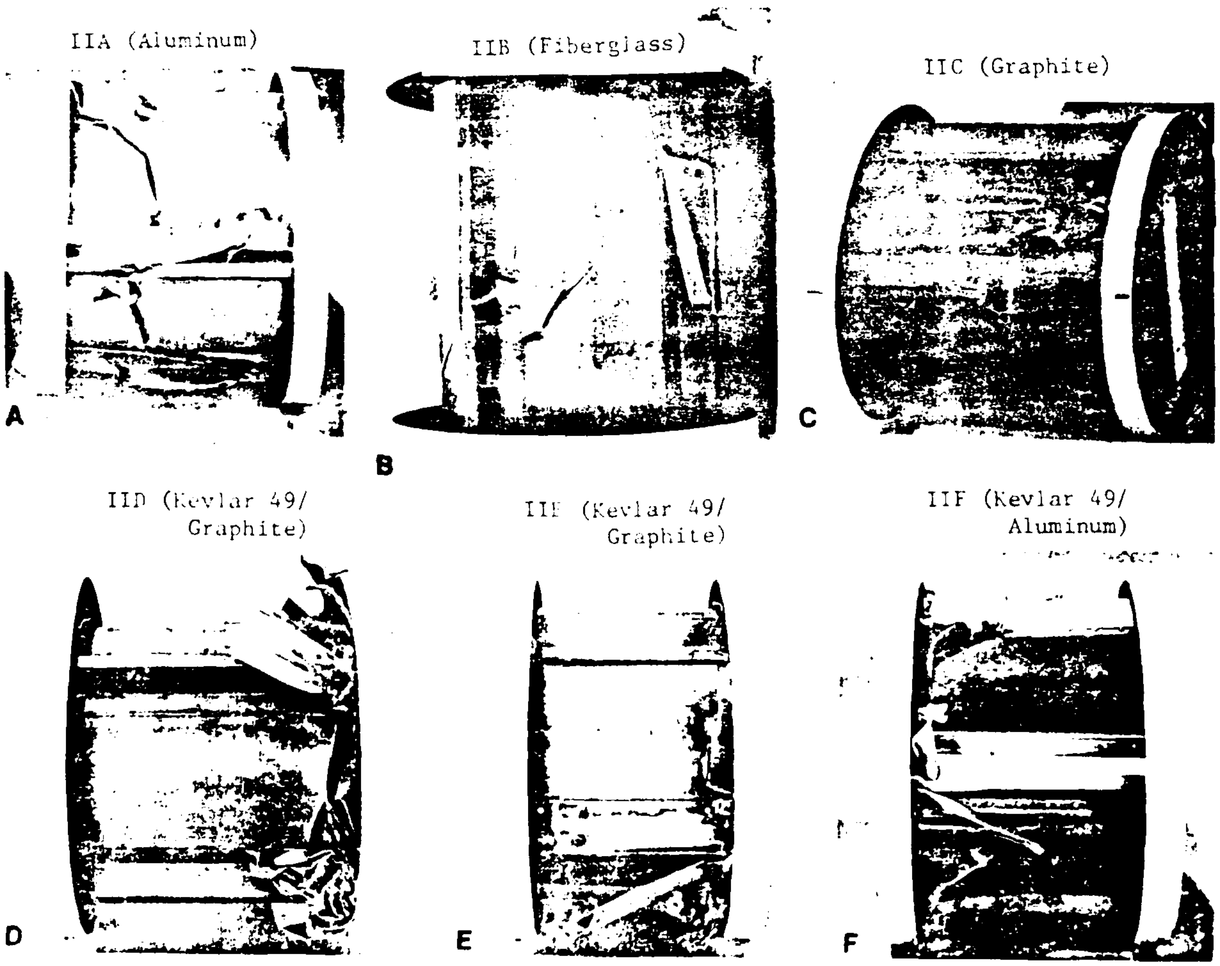


Figure 3.10. Externally Stiffened Specimens After Failure (Ref. 25)

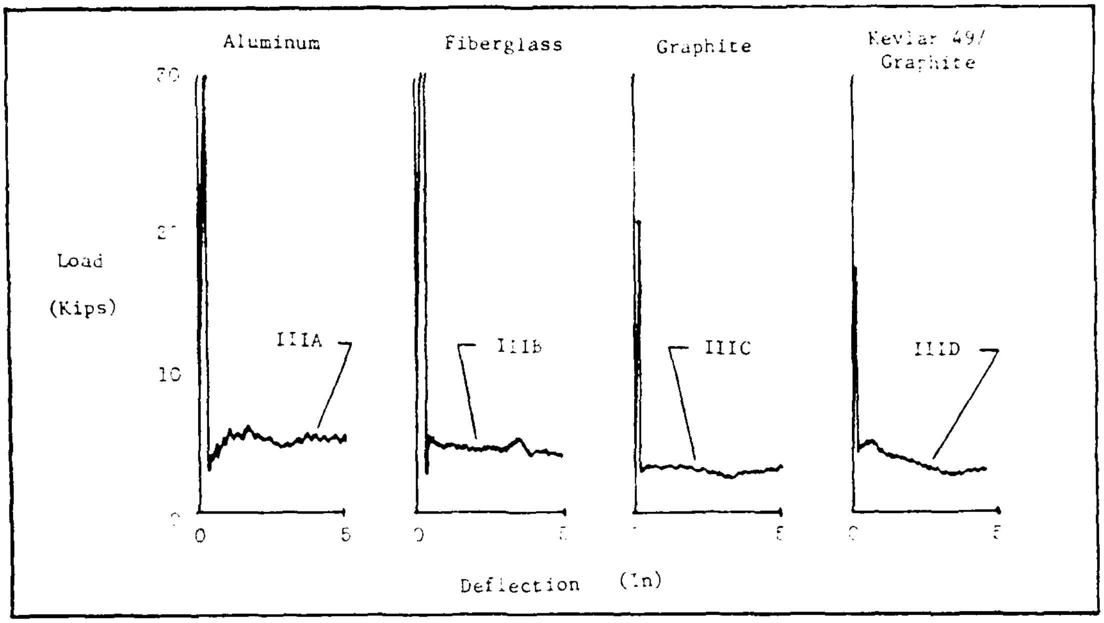


Figure 3.11. Load/Deflection Curves for Honeycomb Sandwich Specimens (Ref. 25)

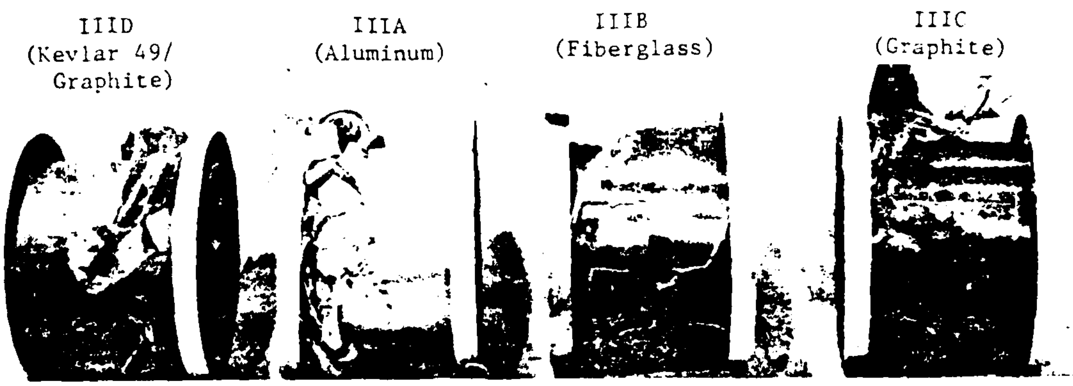


Figure 3.12. Honeycomb Sandwich Specimens After Failure (Ref. 25)

The graphite sandwich specimen failed at 39,500 lbs. as a result of circumferential skin cracking or buckling. The post-ultimate behavior was characterized by cusping of the skin at the points of fracture and progressive delamination of the skin from the core. Energy absorption was much higher than that of the stiffened cylinders.

Similar response was observed for hybrid Kevlar/graphite sandwich design (Fig. 3.12). However, unlike the corresponding stiffened cylinders, considerable tearing of the Kevlar was observed.

The ultimate and average post-ultimate load capacities of all specimens are summarized below.

Test Specimen Load Carrying Capacities

Specimen	Material/ Concept	Ultimate Load (lbs)	Avg Post-Ult. Load (lbs)
IA	AL/IS	27,750	9,000
IB	FG/IS	36,850	4,000
IC	FG/IS	41,900	2,300
ID	GR/IS	----	---
IE	GS/IS	24,350	850
IF	K49/GR/IS	26,700	850
IG	K49/GR/IS	23,400	900
IIA	AL/ES	29,000	5,000
IIB	FG/ES	22,500	1,200
IIC	GR/ES	26,700	1,000
IID	K49/GR/ES	22,950	1,600
IIE	K49/GR/ES*	22,550	1,850
IIF	K49/AL/ES*	21,450	4,500
IIIA	AL/HS	59,950	9,400
IIIB	FG/HS	112,500	8,200
IIIC	GR/HS	39,500	5,600
IIID	K49/GR/HS	33,600	6,400

*Bonded and Riveted

IS - Internal Stringer
ES - External Stringer
HS - Honeycomb Sandwich
AL - Aluminum

FG - Fiberglass Epoxy
GR - Graphite/Epoxy
K49 - Kevlar 49/Epoxy

The skin/stiffener tests show conclusively that unless energy absorption requirements are a design consideration, conventional sheet/stringer aluminum construction is superior to composite sheet/stringer construction regarding compressive energy absorption characteristics.

However, honeycomb sandwich composite skins fared much better in comparisons against aluminum. Thus, it may be possible to match aluminum crash energy absorption without serious weight penalty. These conclusions are summarized in Fig. 3.13.

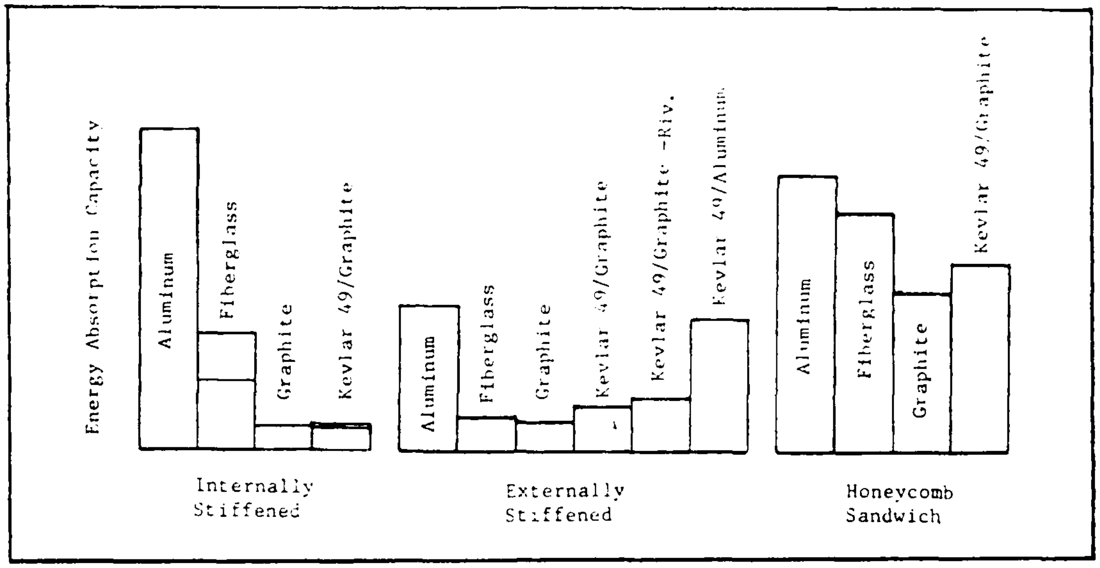


Figure 3.13. Comparison of Energy Absorption Capacity of All Specimens (Ref. 25)

3.2 Impact Resistance of Graphite and Hybrid Configurations

Labor and Bhatia [26] report the results of impact studies on various thin and thick laminates of graphite/epoxy and hybrid configurations. Highlights and excerpts from that paper follow.

The effects of configuration variations on the impact resistance of graphite/epoxy laminates is discussed in [26]. These effects were evaluated by conducting tests on monolithic panels of .04" to .18" thickness and sandwich panels with face sheets of thickness .02" to .5". Additional tests were also conducted on .5" thick monolithic panels typical of aircraft wing structures.

Several materials were investigated to determine their effect on the enhancement of impact resistance of baseline panels. Plies of ductile materials were added to the base graphite/epoxy panel and, in some cases, parts of graphite/epoxy plies were replaced by woven graphite/epoxy.

Impact tests were conducted using a falling weight with sharp and blunt impactors, strain-gauged to give force-time histories during the impact sequence. From these histories, the absorbed energy histories were calculated. Acoustic scans and photomicrographs of cross sections were made to determine the extent of internal damage as well as to identify failure modes.

Internal damage occurred for impacts causing little or no visible exterior damage. Thin laminates had more back surface damage while thick laminates had more front surface damage for damage near the visible threshold.

Impact damage has been shown to cause significant strength losses for composite specimens. However, the strains to failure for impacted specimens are usually above permissible levels currently adopted for design, which are limited by effects of fastener holes and moisture and temperature on matrix properties.

Low velocity impact studies were conducted using instrumented impactors to obtain force and energy values during impact. Several geometric configuration variables have been investigated including panel size, impact location, impactor size and shape, panel thickness, type of edge support, and variations in mass and velocity of the impactor.

Laboratory procedures for simulating impact damage employed three separate impacting systems. A conventional drop tower was used for low speed impacts up to approximately 5 feet per sec. on laminates of thickness ≤ 0.25 in. For .5" thick laminates, a falling mass in a guide tube was used at velocities up to 20 ft. per sec. Both the drop tower and guide tube assemblies used instrumented impactors. A gas gun was used to fire various projectiles to simulate foreign object impact at velocities up to several hundred feet per second.

The drop tower was a DYNATUP Model 8000A. It is a gravity driven device with remote controls for release of the hammer and impactor.

Interchangeable impactors were mounted on the hammer. Semi-conductor strain gauges attached to the neck of the impactor gave a continuous measurement of the contact force between the specimen and the impactor over a period of milliseconds. Integration of the output gives the energy absorbed by the specimen at any instant during the impact.

Most panels were impacted at the center of the five-inch square unsupported area and were impacted four times, once in each bay of the support fixture, with the depth of penetration varied from through-penetration to that causing slightly more than incipient damage.

Foreign object damage studies were conducted with a 1.18 in. diameter gas gun, consisting of a launcher system capable of sabot launching projectiles at velocities from under 100 ft/sec. up to several thousand ft/sec. The gun employs rapid expansion of a highly compressed gas to accelerate the sabot out of the launch tube.

Projectile impact velocity was measured by two laser beams placed along the trajectory at a predetermined distance. A high speed camera was used to determine projectile impact and rebound velocity and to record projectile-panel interaction.

Both impact velocity and angle of incidence were varied and several types of projectiles were used including glass and steel spheres and a granite projectile machined to be cylindrical with conical ends.

Three types of specimens were fabricated and impacted. These are (a) "thin laminates" up to 32 plies (0.176") thick,(b) "thick laminates" (0.5" thick),and (c) "improved concept" laminates in which material or configuration was changed to increase impact resistance.

Table 1. Concepts for Improved Impact Resistance

ADD:	S-Glass cloth (surface and interleaved)
	Kevlar cloth
	Nylon cloth
	Kevlar phenolic (precured)
REPLACE ALL PLIES WITH:	
	Woven Gr/Ep (HMF-133/3501-6)
	Woven 10% S-Glass hybrid
	Woven Gr/Ep (HMF-134/3501-6)
REPLACE TWO SURFACE PLIES WITH:	
	Woven Gr/Ep (HMF-133/3501-6)
	Woven 10% S-Glass hybrid
MISCELLANEOUS CONCEPTS	
	Foam adhesive at core
	Increased core density
	Stiffeners: Foam fill/stapled

EXPERIMENTAL RESULTS

Thin Laminates

The larger panels, or ones with more flexible edge supports, tended to exhibit more flexual deflection during the impact, and as a result, more energy was absorbed prior to the initiation of damage.

Limited tests were made on a few boron/epoxy panels. Comparable impacts against boron and graphite panels indicate that the boron panels absorb less energy to cause incipient damage, evidently the result of stiffer filaments which allow less flexual energy dissipation. Damage typically consists of matrix cracking with no fiber breakage. The damage in the boron panels tends to be more localized with less delamination or splintering away from the point of impact.

Stiffened panels were impacted over the stiffener attachment on the side of the panel opposite the stiffener. The stiffener debonded slightly at incipient damage, and at more severe loading debonded over an extended length. Incipient damage for the riveted stiffener consisted of minor matrix cracking in the stiffener at the rivets adjacent to the impact. The riveted stiffener absorbed 43 per cent more energy at incipient damage and also showed a less critical type of damage, and is therefore considered superior for impact resistance. The effect of the rivet holes on the panel strength may affect the choice of stiffener attachment for a specific application.

All sandwich panels had a core thickness of 0.5 inches. Incipient damage for these occurs at very low energy levels. Local crushing of the core occurs first but face sheet cracking and delamination also occur at low energy levels.

A comparison of an eight ply sandwich panel having 6.1 pcf core with an eight ply monolithic (non-sandwich) panel indicates that the monolithic panel absorbed nearly five times as much energy to initiate damage. In the monolithic panel, the initial damage occurs by splitting the back face between the fibers, thus requiring more energy than to crush the honeycomb in the sandwich panel.

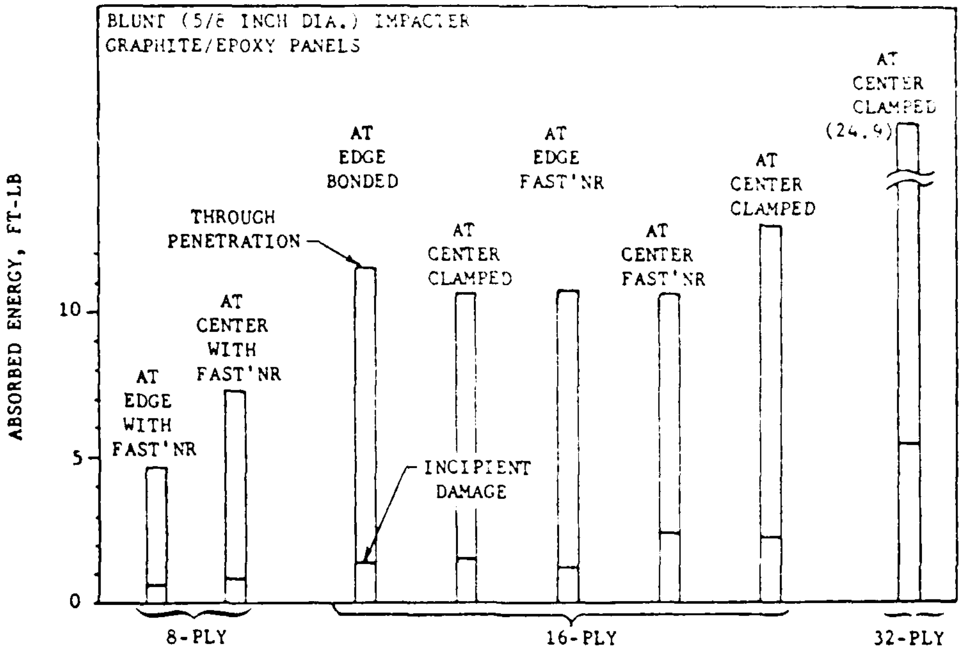


Figure 3.14. Baseline Monolithic Panel Surface Impact Data (Ref. 26)

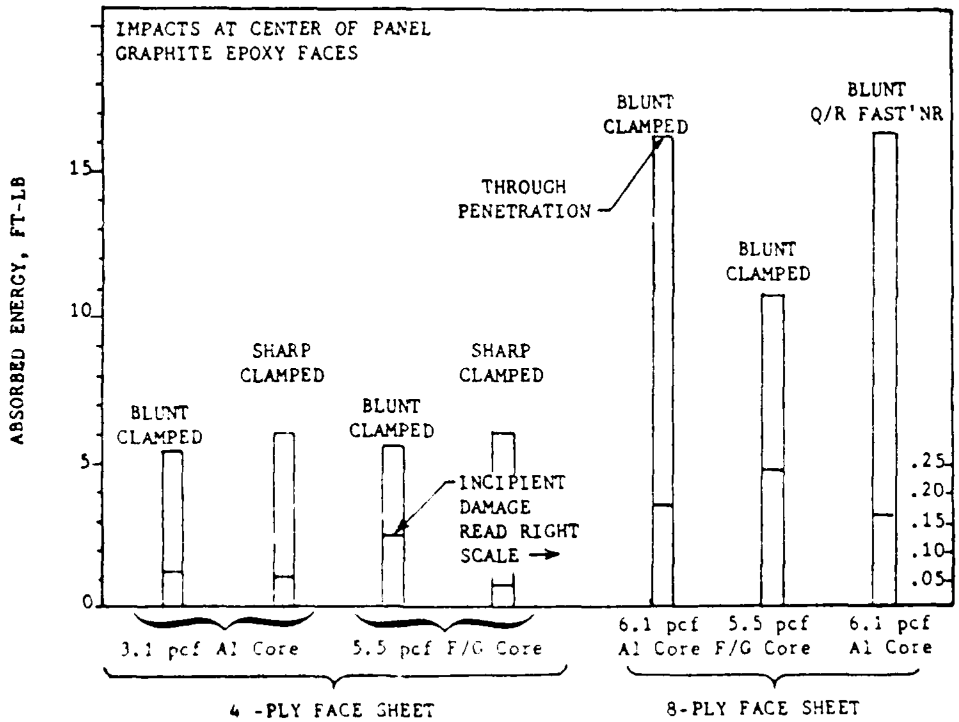
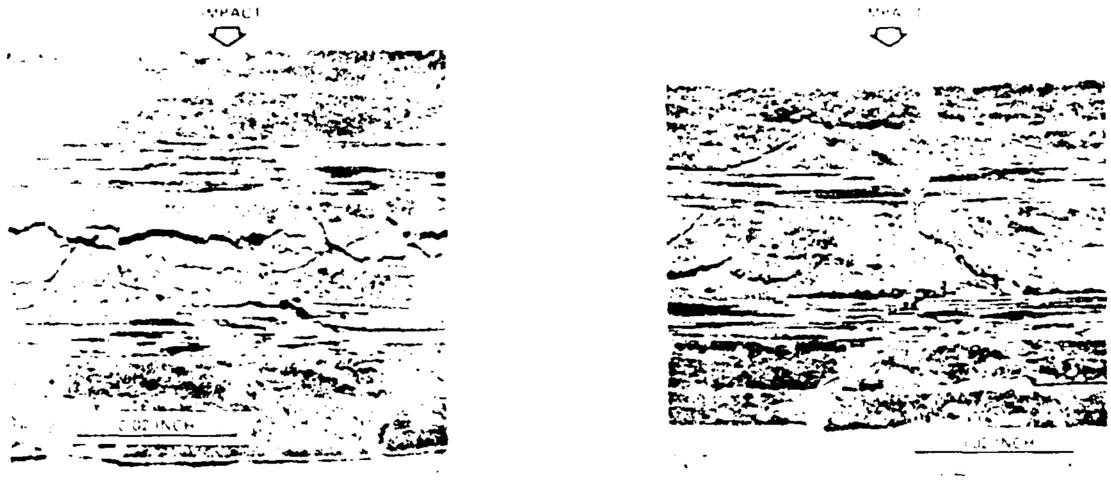


Figure 3.15. Baseline Sandwich Panel Surface Impact Data (Ref. 26)

Foreign object damage testing was conducted to determine whether high velocity impact would significantly affect panel impact damage. All FOD specimens were six inches square and were clamped in a fixture which left a five inch square unsupported area. Impacts were conducted on eight-ply and 16-ply monolithic panels and on aluminum honeycomb sandwich panels with four-ply and eight-ply face sheets. Glass and steel spherical projectiles were used as well as cylinders of glass or granite with cone-shaped ends. Projectiles were 3/8 inch and 5/8 inch in diameter. Both 90° and 45° impact angles were used with velocities ranging from 52 ft/sec to 480 ft/sec.

Photomicrographs of cross sections through the impact areas were made for several specimens to observe failure modes (Fig. 3.16).



8 PLIES GR-EP (±45/0/90)$_s$

BLUNT IMPACTOR AT CENTER OF 5 INCH SQUARE AREA
TOTAL ABSORBED ENERGY - 1.24 FT-LB
(INCIPIENT DAMAGE INDICATED AT 0.82 FT-LB)
DAMAGE NOT VISIBLE ON IMPACTED SURFACE
SLIGHT MATRIX CRACK ON BACK FACE

8 PLIES GR-EP (±45/0/90)$_s$

SHARP IMPACTOR AT CENTER OF 5 INCH SQUARE AREA
TOTAL ABSORBED ENERGY - 0.43 FT-LB
(INCIPIENT DAMAGE INDICATED AT 0.40 FT-LB)
DAMAGE NOT VISIBLE ON IMPACTED SURFACE
SLIGHT MATRIX CRACK ON BACK FACE

Figure 3.16. Photomicrographs of Impact Areas of 8-Ply Panels (Ref. 26)

Although delamination is probably the dominant failure, considerable matrix cracking is also evident, and broken fibers can be seen in internal plies even though fibers are not broken in the surface plies. Thinner panels show more delamination, probably because they flex locally under the impact, thus developing high interlaminar shear stresses which cause delamination.

Thick Laminates

Because of their greater thickness, considerably higher energy levels were required to cause damage in the 1/2-inch thick laminates. The major difference in comparisons with thin laminates was the variation in the amount of damage on the front and back faces and internally.

For impact energy less than 30 ft-lbs, the low velocity impacts cause smaller damage sizes for center impacts, which is probably a result of more energy being used for flexual deflection at the lower velocities. The data demonstrate the complexity of the impact phenomenon and suggest that damage size is affected by a number of parameters, including impact location, panel thickness, impactor shape and size, flexual deflection and velocity of impact.

Improved Impact Resistance Laminates

The effects of concepts which add one ply of S-glass to monolithic panels are shown in Fig. 3.17.

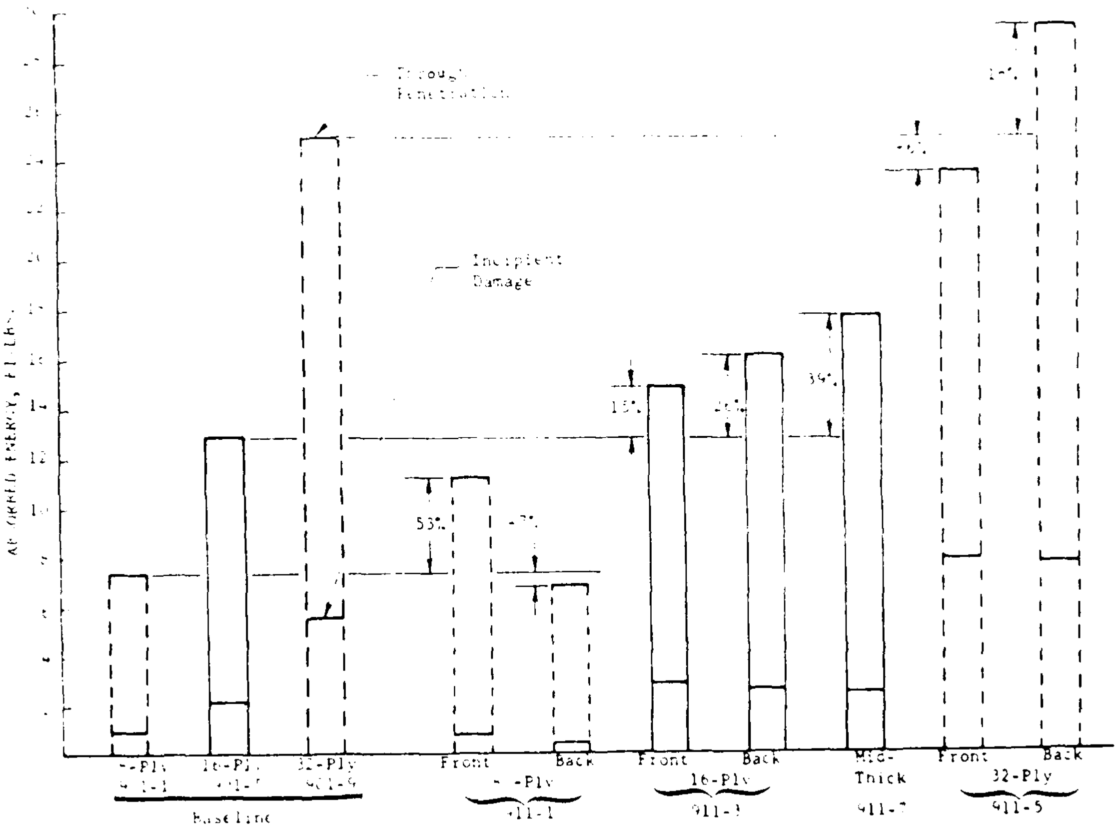


Figure 3.17. Effect of Concepts Which Add One S-Glass Ply to Monolithic Panels (Ref. 26)

The energies required for complete penetration and incipient damage are shown. Data for baseline panels are shown for 8-, 16-, and 32-ply panels made of AS/3501-5 tape material. The results of tests on improved concept panels are compared with the baseline data.

Data are shown in Fig. 3.18 for the addition of one ply of either Kevlar or ballistic Nylon. The Kevlar bidirectional woven cloth was prepregged with 3501-6 resin and laid up and cured with the basic graphite/epoxy tape. The 12-ounce per sq. yd. ballistic Nylon was not prepregged, but was laid directly on the graphite/epoxy tape.

When on the back surface, the Kevlar ply is effective in limiting the damage to a localized area. The Nylon on the back surface delaminated over a larger area than the corresponding Kevlar ply. Undoubtedly some of the

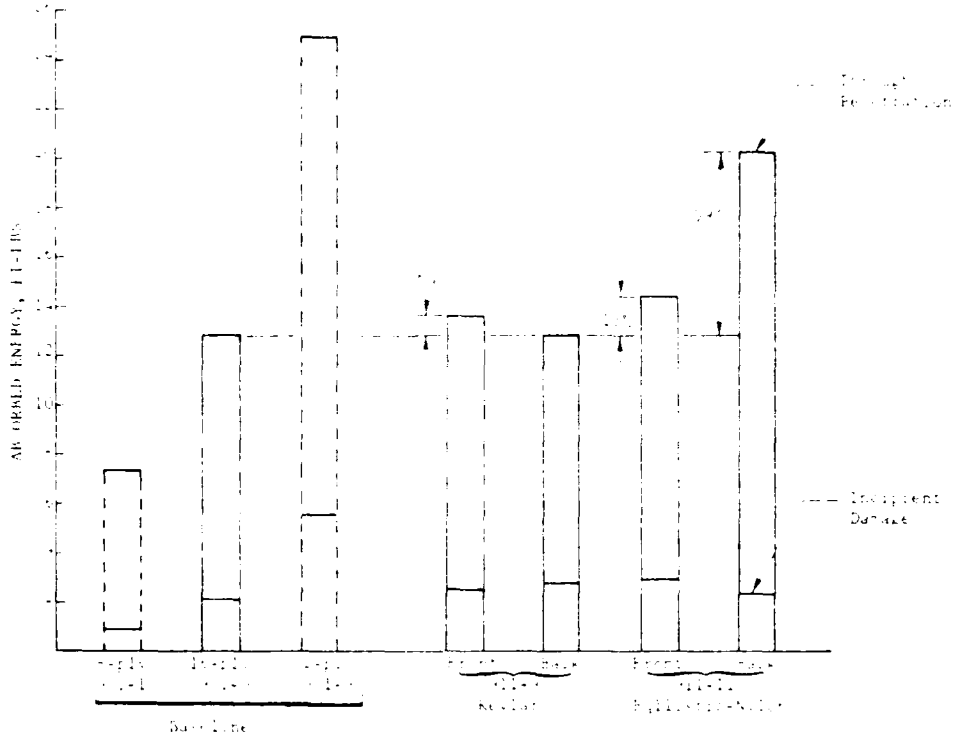


Figure 3.18. Effect of Concepts Which Add One Ply of Kevlar or Ballistic Nylon to 16 Ply Monolithic Panels (Ref. 26)

extra energy absorbed by the ballistic Nylon panel was used in causing this increased delamination which is not advantageous since it tends to increase the size of the damaged zone. Neither Kevlar nor ballistic Nylon was effective in concealing damage when used on the front surface.

Adding surface plies of a ductile material such as glass or Kevlar increases the energy required to cause incipient damage by about the same amount as adding a comparable thickness of the basic material. The ductile materials, however, can help to contain damage. Development of more ductile resin systems or techniques to increase the interlaminar and intralaminar shear and tensile strengths of the matrix seem to offer promise of significantly increased incipient damage energy level.

3.3 Effects of Elastomeric Additives on the Mechanical Properties of Epoxy Resin and Composite Systems

Moulton and Ting [27] report studies exploring the use of elastomeric additives to improve the toughness of epoxy resin and composite systems. A concise summary of that paper follows.

Thermosetting resins such as epoxy and polyimide are widely used as matrix materials in organic composites. These polymers are brittle materials with low resistance to flaw growth and crack propagation. A remedy is the addition of elastomeric particles to the brittle matrix to improve resin toughness. The mechanisms for this enhancement involve triaxial dilatation of rubber particles at crack tips, particle shearing, and matrix plasticity. In [27], the fracture behavior and mechanical properties of such enhanced composites have been investigated experimentally.

A series of acrylonitrile-butadiene modified epoxy polymers were investigated. Resin fracture energies were determined by testing standard compact tension specimens and Izod impact specimens. The elastomeric additives greatly increased the fracture energies of the base epoxy. Laminates consisting of 7781 glass and T300/3K graphite were used. Enhanced toughness is observed to correlate with decreased strength and modulus. Elastomeric additives were found to improve laminate fatigue life by a factor of ten. Thus the modified composites have a considerably improved fatigue design limit, with a trade-off in strength.

Increased toughness does not come without some sacrifice of initial matrix-controlled mechanical properties. Interlaminar strength (short beam shear test), high temperature strength retention, and wet strength retention are examples of matrix-controlled properties. Ultimate compression and flexural strengths are also heavily influenced by matrix properties. Generally the modulus of the resin is lowered in proportion to the volume content of the second phase. The second phase evidently reduces the initial load bearing surface area.

Lowering the modulus can actually increase some fiber-controlled initial properties such as tensile strength, and improve matrix-controlled properties where the strain-to-failure is critical (e.g. off-axis tensile, transverse tensile, and flexural fatigue properties).

An added benefit of composite toughening is improved laminate processability, particularly in applications involving complex curvatures and varying thicknesses.

All elastomer epoxy compositions showed a decrease in fracture energy (energy required to initiate dynamic fracture propagation) with increasing strain rate. It seems that the second phase has a time dependent capability to distribute stress and toughen.

The toughness of the resin should be at least 1 kJ/m^2 so that, when a composite with woven fiber is made, the lay up geometry and fiber volume fraction will not affect flow sensitivity. Approximately 5% matrix strain will be required to prevent premature interface failure due to uneven stress concentration between fibers under transverse stress conditions. The second phase appears to dominate critical fracture energy, but only moderately affects high rate stresses such as impact. This is because the second phase requires time for its various deformation mechanisms to become operative for energy dissipation.

3.4 Unsymmettrical Buckling of Laterally-Loaded, Thin, Initially-Imperfect, Orthotropic Plates

In Ref. 28, Marshall presents a theoretical analysis for unsymmetrical bifurcation buckling of thin initially-imperfect orthotropic plates loaded laterally on the convex face. Unsymmetrical buckling is shown to be a function of the plate's initial geometry and to reduce greatly the effective load-bearing capacity.

The effect of geometrical imperfections in plates has received considerable attention. However, prior investigations have been primarily concerned with isotropic materials while anisotropic materials have received comparatively little attention.

The von Karman large deflection compatibility equation for the case of an orthotropic plate with an initial imperfection is

$$\frac{\partial^4 F}{\partial x^4} + \alpha \frac{\partial^4 F}{\partial x^2 \partial y^2} + \beta \frac{\partial^4 F}{\partial y^4}$$

$$= E_y \left[\left(\frac{\partial^2 w}{\partial x \partial y} \right)^2 - \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} + 2 \frac{\partial^2 w_o}{\partial x \partial y} \frac{\partial^2 w}{\partial x \partial y} + \frac{\partial^2 w_o}{\partial x^2} \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w_o}{\partial y^2} \frac{\partial^2 w}{\partial x^2} \right] \tag{1}$$

where F is the Airy stress function, $\alpha = (E_y/G) - 2\nu_y$, $\beta = E_y/E_x$, w is the plate deflection, w_o is the initial imperfection, the E's are elastic moduli, G is the shear modulus, ν_y is Poisson's ratio transverse to the direction of reinforcement. The total potential consists of the energy of midplane stretching U_s, bending energy U_b, and the load potential U_p: $U_t = U_s + U_b + U_p$ where

$$U_s = \frac{h}{2} \iint_A \left[\frac{1}{E_x} \left(\frac{\partial^2 F}{\partial y^2} \right)^2 - 2 \frac{\nu_x}{E_x} \frac{\partial^2 F}{\partial x^2} \frac{\partial^2 F}{\partial y^2} + \frac{1}{G} \left(\frac{\partial^2 F}{\partial x \partial y} \right)^2 + \frac{1}{E_y} \left(\frac{\partial^2 F}{\partial x^2} \right)^2 \right] dx\, dy \tag{2}$$

$$U_b = \frac{1}{2} \iint_A \left[D_1 \left(\frac{\partial^2 w}{\partial x^2} \right)^2 + 2 D_3 \frac{\partial^2 w}{\partial x \partial y} + D_2 \left(\frac{\partial^2 w}{\partial y^2} \right)^2 \right] dx\, dy \tag{3}$$

$$U_p = - \iint_A w\, q_z \, dx\, dy \tag{4}$$

where q_z is transverse loading intensity, D_1 = plate flexural rigidity in x-direction (similarly for D_2 in y-direction) and D_3 = plate twisting rigidity, h = plate thickness. It is assumed that the deflection and stress function can be expanded in double series

$$w(x,y) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} w_{mn}\, m(x)\, n(y) \tag{5}$$

$$F(x,y) = \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} F_{jk}\, j(x)\, k(y) \tag{6}$$

It is assumed that the plate is simply supported:

$$x=0,a:\ w=0\ ,\ \frac{\partial^2 w}{\partial x^2}+\nu_y\frac{\partial^2 w}{\partial y^2}=0\ ;\ \frac{\partial^2 F}{\partial y^2}=0,\ \frac{\partial^2 F}{\partial x\,\partial y}=0 \tag{7}$$

$$x=0,b:\ w=0\ ,\ \frac{\partial^2 w}{\partial y^2}+\nu_x\frac{\partial^2 w}{\partial x^2}=0\ ,\ \frac{\partial^2 F}{\partial x^2}=0\ ,\ \frac{\partial^2 F}{\partial x\,\partial y}=0 \tag{8}$$

One may choose

$$w(x,y)=\sum_{m=1}^{2}\sum_{n=1}^{1} w_{mn}\ \sin\frac{m\pi x}{a}\ \sin\frac{n\pi y}{b} \tag{9}$$

$$F(x,y)=\sum_{j=1}^{1}\sum_{k=1}^{1} F_{jk}\left[\cos\frac{j\pi x}{a}-1\right]\left[\cos\frac{k\pi y}{b}-1\right] \tag{10}$$

$$w_o(x,y)=\sum_{p=1}^{2}\sum_{q=1}^{1} w_{o_{pq}}\ \sin\frac{p\pi x}{a}\ \sin\frac{q\pi y}{b} \tag{11}$$

Since these truncated series cannot satisfy the boundary conditions, a solution is sought using the Galerkin method:

$$\begin{aligned}\iint_A\left(\frac{\partial^4 F}{\partial x^4}+\alpha\frac{\partial^4 F}{\partial x^2\partial y^2}+\beta\frac{\partial^4 F}{\partial y^4}\right)\ell(x)\,t(y)\,dx\,dy\\ =\iint_A\Bigg[\left(\frac{\partial^2 w}{\partial x\,\partial y}\right)^2-\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}-2\frac{\partial^2 w_o}{\partial x\,\partial y}\frac{\partial^2 w}{\partial x\,\partial y}\\ +\frac{\partial^2 w_o}{\partial x^2}\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w_o}{\partial y^2}\frac{\partial^2 w}{\partial x^2}\Bigg]\ell(x)\,t(y)\,dx\,dy\end{aligned} \tag{12}$$

where $\ell(x)$, $t(y)$ are weighting functions. Substituting (9), (10), (11) into (2), (3), (4) and noting (12), the total potential of the loaded plate can be written in terms of deflection function coefficients only. For uniform pressure loading, one obtains

$$\begin{aligned}U_t=&\frac{\pi^4\lambda E_y h}{8(3+\alpha\lambda^2+3\beta\lambda^4)^2}\Bigg[\frac{w_{11}^4}{4}+w_{11}^2w_{21}^2-w_{11}^3w_{o_{11}}-2w_{11}^2w_{21}w_{o_{21}}\\ &+w_{21}^4-2w_{11}w_{o_{11}}w_{21}^2-4w_{21}^3w_{o_{21}}+w_{11}^2w_{o_{11}}^2\\ &+4w_{11}w_{o_{11}}w_{21}w_{o_{21}}+4w_{21}^2w_{o_{21}}^2\Bigg]\\ &+\frac{\pi^4E_y h^3}{96\lambda^3(1-\nu_x\nu_y)b^2}\left[w_{11}^2\left(\frac{1}{\beta}+\frac{2D_3}{D_2}\lambda^2+\lambda^4\right)\right]\\ &+\frac{\pi^4E_y h^3}{12\lambda^3(1-\nu_x\nu_y)b^2}\left[w_{21}^2\left(\frac{2}{\beta}+\frac{D_3}{D_2}\lambda^2+\frac{\lambda^4}{8}\right)\right]-4w_{11}\frac{ab}{\pi^2}q_z\end{aligned} \tag{13}$$

where λ = plate aspect ratio a/b.

Minimizing V_t with respect to each of the w_{ij} yields two nonlinear algebraic equations which were solved by the method of successive substitutions. Solutions for various symmetric and asymmetric initial imperfection modes have been summarized graphically in [28], where excellent agreement with experiments and previous theoretical investigations has been noted.

3.5 Finite Element Analysis of Instability-Related Delamination Growth

A study of postbuckled through-thickness delamination in laminated coupons was performed by linear and geometrically nonlinear finite element analysis and reported by Whitcomb in Ref. 29. The analysis was verified by comparisons with exact solutions for simple geometries. Also, measured lateral deflections of postbuckled through-width delaminations were compared with numerical predictions.

Local buckling of delaminated plies in composite laminates can precipitate rapid delamination growth and attendent structural collapse. It is fruitful then to consider the characterization and prediction of such local effects so that the effects of delamination can be predicted. In [29] a two-dimensional finite element analysis was developed to study the postbuckling behavior of delaminations. A resume of the relevant analysis is given here. The basis of the analysis is the principle of minimum total potential energy where the total potential Π is given by

$$\Pi = \frac{w}{2}\int \sigma_{ij}\,\epsilon_{ij}\,dA - W$$

where w is the lamina width and W is the potential of the conservative loads. Here ϵ_{ij} are related to the displacements u_i by

$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i}\frac{\partial u_k}{\partial x_j}\right)$$

The actual displacements u_i are related to the finite element degrees of freedom u_i^α by

$$u_i = N^\alpha\, u_i^\alpha \qquad \text{(sum on } \alpha\text{)}$$

Minimizing Π above with respect to the u_i^α gives

$$w\int \sigma_{ij}\,\frac{\partial \epsilon_{ij}}{\partial u_n^\beta}\,dA = P_n^\beta$$

The assembled nonlinear equations are solved iteratively by the Newton-Raphson method. This requires calculation of the element tangent stiffness matrix K_t:

$$\left(K_t\right)_{mn}^{\theta\lambda} = w\,\frac{\partial}{\partial u_m^\theta}\left(\int \sigma_{ij}\,\frac{\partial \epsilon_{ij}}{\partial u_n^\lambda}\,dA\right)$$

$$\equiv \left(K_0\right)_{mn}^{\theta\lambda} + \left(K_1\right)_{mn}^{\theta\lambda} + \left(K_\sigma\right)_{mn}^{\theta\lambda}$$

where

$$(K_c)^{\theta\lambda}_{mn} + (K_L)^{\theta\lambda}_{mn} = w \int C_{ijkl} \frac{\partial \epsilon_{kl}}{\partial u^{\theta}_{m}} \frac{\partial \epsilon_{ij}}{\partial u^{\lambda}_{n}} \, dA$$

and

$$(K_\sigma)^{\theta\lambda}_{mn} = w \int \delta_{mn} \, \sigma_{ij} \frac{\partial N^{\lambda}}{\partial x_i} \frac{\partial N^{\theta}}{\partial x_j} \, dA$$

The experimental specimen used to verify the computations consisted of four-ply unidirectional graphite/epoxy bonded to 2024-T3 AL with EA934 adhesive. The adhesive was cured at room temperature. To simulate a delamination, teflon tape was used to prevent bonding in the central part of the specimen.

Some of the specimens were loaded statically so that lateral deflections could be measured with a micrometer. Five fatigue specimens were tested under constant-amplitude, load controlled sinusoidal in-plane loading.

The present numerical analysis was verified by analyzing two problems for which exact solutions are available. Also, comparison of measured and predicted lateral deflections of post-buckled through-width delaminations corroborated the numerical predictions. A small number of specimens were were fatigue tested to obtain delamination growth data. Calculated strain-energy release rates were qualitatively correlated with the observed growth rates to determine the relative importance of Mode I (opening) and Mode II (sliding) components of strain-energy release rates.

Load transfer near the delamination was very complex. Interlaminar stresses were not a simple function of applied load or lateral deflection. Very steep gradients in the calculated stresses at the delamination front suggested the presence of a stress singularity. Hence the peak values of interlaminar stresses have little meaning, since they depend on mesh refinement. However, strain-energy release rates are much less sensitive to mesh refinement than calculated stresses.

Calculated strain-energy release rates for Mode I and Mode II crack extension were very sensitive to delamination length, delamination depth, and load level. The Mode I strain energy release rate (G_I) increased with increasing load and lateral deflection initially but then decreased, while the Mode II rate (G_{II}) increased monotonically with increasing load. If the structure had responded linearly G_I would have increased monotonically with the square of the load, and the ratio G_I/G_{II} would have remained fixed. For a given lateral deflection, G_I was greater for shorter and deeper delaminations. For fixed remote loading G_I was not necessarily greater or smaller for the shorter and deeper delaminations.

Qualitative correlation of calculated G_I and G_{II} values with observed delamination growth rates showed that delamination growth is dominated by G_I, even though numerically G_{II} may be much larger. Because G_I is not a simple function of delamination length, delamination depth, applied load or lateral deflection, predicting growth rates from limited delamination growth data is expected to be difficult and subject to significant error.

3.6 Elastic-Plastic Flexural Analysis of Laminated Composite Plates by the Finite Element Method

With the increasing use of composite materials in structural applications, the need for elastic-plastic analysis of ductile composites grows with the development of new laminated systems, and applications which require more demanding specifications. An elastic-plastic flexural plate finite element is formulated by combining the theory of plasticity for homogeneous materials with classical laminated plate theory, and is presented by Mahmoud in Ref. 30.

The laminated rectangular plate element consists of a number of layers bonded together so that the plate behaves kinematically as a unit. Each layer is unique and is assumed to have effective material properties permitting the assumption of overall homogeneity. Here the layers are assumed to be isotropic. The strain increments are decomposed into elastic and plastic parts, viz. (subscript m identifies the m^{th} layer).

$$\Delta \boldsymbol{\epsilon}_m = \Delta \boldsymbol{\epsilon}_m^e + \Delta \boldsymbol{\epsilon}_m^p \tag{1}$$

The incremental constitutive relationship is

$$\Delta \boldsymbol{\epsilon}_m = \left(\boldsymbol{C}_m^e + \boldsymbol{C}_m^p \right) \Delta \boldsymbol{\sigma}_m \tag{2}$$

with

$$\boldsymbol{C}^p = \frac{1}{H \sigma_e^2} \begin{bmatrix} (\sigma_x - \frac{1}{2}\sigma_y)^2 & (\sigma_x - \frac{1}{2}\sigma_y)(\sigma_y - \frac{1}{2}\sigma_x) & 3\sigma_{xy}(\sigma_x - \frac{1}{2}\sigma_y) \\ & (\sigma_y - \frac{1}{2}\sigma_x)^2 & 3\sigma_{xy}(\sigma_y - \frac{1}{2}\sigma_x) \\ \text{SYMM} & & (3\sigma_{xy})^2 \end{bmatrix} \tag{3}$$

where H is the slope of equivalent stress, equivalent plastic strain curve with

$$\sigma_e^2 = \sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\sigma_{xy}^2 \tag{4}$$

The Kirchhoff hypothesis gives

$$\Delta \boldsymbol{\epsilon} = z \Delta \boldsymbol{\chi} \tag{5}$$

where z is the thickness coordinate and $\Delta\boldsymbol{\chi}$ is the vector of midsurface curvature increments. Substituting (5) into (2) gives

$$\Delta \boldsymbol{\sigma}_m = z\, \boldsymbol{D}_m \Delta \boldsymbol{\chi} \quad ; \quad \boldsymbol{D}_m = \left(\boldsymbol{C}_m^e + \boldsymbol{C}_m^p \right)^{-1} \tag{6}$$

The moment resultants are then

$$\Delta \boldsymbol{M} = \boldsymbol{D}\, \Delta \boldsymbol{\chi} \tag{7}$$

where

$$\boldsymbol{D} = \sum_{m=1}^{n} \left(\int_{z_{m-1}}^{z_m} z^2\, \boldsymbol{D}_m\, dz \right) \tag{8}$$

The finite element interpolations give

$$\Delta \underset{\sim}{\wedge} = \underset{\sim}{B} \ \Delta \underset{\sim}{d} \tag{9}$$

where $\Delta \underset{\sim}{d}$ are the incremental generalized degrees of freedom. Then the element stiffness is

$$\underset{\sim}{K} = \int_A \underset{\sim}{B}^T \underset{\sim}{D} \ \underset{\sim}{B} \ dA \tag{10}$$

After application of each load increment, each layer is checked in order to update the constitutive matrix and the stiffness matrix. The solution method outlined here is the linear incremental method.

The model presented here has demonstrated very good agreement in comparisons with experimental data obtained for aluminum-aluminum oxide sandwich composites.

3.7 Behavior and Analysis of Bolted Joints in Composite Laminates

The joining of and load transfer between composite material structural components have been studied extensively both experimentally and analytically to develop effective joining procedures and to obtain an understanding of the physical behavior of the structure throughout the joint region. For example, Oplinger [31] has reported extensive experimental and theoretical studies of the behavior of various types of fastener arrangements. Wong and Matthews [32] and Soni [33] report examples of finite-element analyses for the stresses and strains in the vicinity of bolted joints.

Oplinger [31] reports the application of both finite-element methods and complex-variable/boundary-callocation methods to analyze the two-dimensional stresses in orthotropic plates with fasteners. Stress concentration factors in the plate adjacent to the fastener were evaluated and the effects of variations of plate orthotropic properties were demonstrated. Both glass/epoxy and graphite/epoxy plates were included. Extensive experimental studies of joint strength for single-fastener lugs are reported for both glass/epoxy and graphite/epoxy to assess the effects of the ratio of fastener diameter D to panel width W for various values of fastener-center to plate-edge distance e, for $e/W \geq 1$. When one evaluates joint design for an array of parallel fasteners based upon results for a single-pin fastener, allowance must be made for the fact that fasteners in parallel may give higher net tension strength and lower bearing strength than single-fastener lugs [31].

Also reported in Ref. 31 are experimental studies of the strength of series (rather than parallel) type fasteners. These fasteners experience a significant variation of load from fastener to fastener. Hence it is shown that the use of elongated holes alleviates the stress concentrations and improves the strength of the overall joint.

Single-fastener studies of laminates such as $0_2/\pm 45°$ where the principal Young's modulus along the 0° fiber is very different from that along the fiber in the 45° plies can reduce the net-section stress concentration factor significantly. Thus, the use of various different composite plies (i.e., hybrid material layups) can be very effective in improving tension strength. However, this can lead to increases in the shear stress concentration factor

[31]. Reference 31 also presents a set of failure rules for bolted joints, and demonstrates that the Nuismer-Whitney rule is observed to agree well with experimental results. Finally, it is noted that ±45° and 0/90° laminates which exhibit ductibility in tension and shear, respectively, show significant reductions in stress concentrations because of this ductility; the ±45° laminates exhibit nonlinear deformation in the net section which resembles that in metallic joints, while 0/90° laminates exhibit plug formation in front of the fasteners.

3.8 Vibration, Buckling, and Postbuckling Studies of Composite Plates

There are numerous papers on the vibration and buckling behavior of composite plates. Also in recent years a considerable amount of experimental and theoretical work has been done on the postbuckling behavior of composite plates; this type of behavior is expected to be observed frequently in the crash responses of composite structures. Two representative recent papers on these topics are those of Leissa [34] and Starnes, Knight, and Rause [35]. The essence of those papers is captured in the following abstracts from these two papers.

Abstract from Ref. 34

Advances in the understanding of vibration and buckling behavior of laminated plates made of filamentary composite material are summarized in this survey paper. Depending upon the number of laminae and their orientation, vibration and buckling analyses of composite plates may be treated with: (1) orthotropic theory, (2) anisotropic theory, or (3) more complicated, general theory involving coupling between bending and stretching of the plate. The emphasis of the present overview is upon the last. Special consideration is given to the complicating effects of: inplane initial stresses, large amplitude (nonlinear) transverse displacements, shear deformation, rotary inertia, effects of surrounding media, inplane nonhomogeneity and variable thickness. Nonclassical buckling considerations such as initial imperfections are included, as well as postbuckling behavior.

Abstract from Ref. 35

Results of an experimental study of the postbuckling behavior of selected flat stiffened graphite-epoxy panels loaded in compression are presented. The postbuckling response and failure characteristics of undamaged panels and panels damaged by low-speed impact are described. Each panel had four equally-spaced I-shaped stiffeners and 16- or 24-ply quasi-isotropic skins. Panels with three different stiffener spacings were tested. Some undamaged specimens supported as much as three times their initial buckling load before failing. Failure of all panels initiated in a skin-stiffener interface region. Analytical results obtained from a nonlinear general shell finite element analysis computer code correlate well with typical postbuckling test results up to failure. The analytical modeling detail necessary to predict accurately the response of a panel is described. Test results show that low-speed impact damage can reduce the postbuckling strength of a stiffened panel and that the skin-stiffener interface region is more sensitive to impact damage than the skin midway between stiffeners.

SECTION 4

REVIEW OF TRANSIENT STRUCTURAL RESPONSE ANALYSIS METHODS

4.1 Introduction

Methods for the theoretical prediction of nonlinear transient structural responses of the type and extent produced by severe impact, blast, or other loads are needed for many uses. Such methods can be used for parametric and/or preliminary design studies or to aid in the design of transient structural response experiments and in estimating the response levels which instrumentation is intended to record. However, there are many structures of interest whose complexity is such that mathematical modeling to provide fine details of transient response would be either prohibitively expensive and/or impractical because of the lack of adequate knowledge to permit proper modeling. Thus, theoretical analysis must be applied appropriately and with discretion. The use of such methods can help limit the scope of mechanical experimentation, but the use of well-designed and carefully-conducted experiments will always be necessary to determine and/or verify many important details of the nonlinear transient structural responses of either complex built-up metallic or of composite-material structures of the type found in aircraft and automotive applications. Well-designed and conducted experiments are essential for validating the final design in this type of nonlinear structural response problem.

In the following, attention is confined to discussing transient structural response prediction methods. It is convenient to discuss these methods in two regimes: (a) linear and (b) nonlinear. Historically, the simpler linear response methods were explored and developed first; then the methods were extended and modified to accommodate nonlinear geometric and/or material behavior.

Linear transient structural response prediction methods consist of three* types:

1. Conventional Lumped Parameter (CLP) wherein the structure is modeled by an appropriate collection of generalized masses connected by linear stiffness elements (beams, springs, etc.).
2. Finite Difference (FD) method wherein the governing differential equation of equilibrium of each structural region is approximated by spatial finite difference expressions in terms of displacement data at the grid stations, with appropriate compatibility enforced.
3. Finite Element (FE) method wherein the various regions of the structure are modeled spatially by appropriate finite elements with appropriate compatibility enforced.

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*All three of these approaches may be applied to either a very simple or a very complex structure.

In eash case, one obtains a set of coupled total differential equations of motion which subsequently can be solved by using an appropriate timewise finite-difference or timewise finite-element solution procedure. Of course, if one wishes to do so, these equations can be recast into normal-mode form and solved timewise analytically since linear transient response is involved.

For the linear transient response regime, the CLP and the FD methods are embodied in dozens of computer programs which have been applied extensively. Hundreds of computer programs based upon the use of the FE method exist and are used most commonly today because of available computing facilities and because of the fact that the FE method permits the analyst to approximate and represent his structure readily geometrically.

Turning next to the nonlinear transient response regime, the FD and the FE method have been applied successfully in a direct and straightforward fashion to relatively simple structures such as beams, plates, cylindrical shells, curved shells, and shells of revolution; nonlinear material behavior, large deflections, buckling failure, and postbuckling behavior have been accommodated and represented properly. However, for complex built-up structures, practical feasibility dictates that one employ a modification of the basic CLP, FD, or FE methods to represent and approximate in a practical way the overall postfailure, unloading, reversed loading, reloading, ... load deflection behavior of certain automatically-selected regions of the structure. This type of approximation feature is currently termed the hybrid approach. This hybrid approach is most commonly employed in conjunction with either the CLP or the FE method. Accordingly, the essential features of these two schemes (CLP/Hybrid and FE/Hybrid) for predicting the nonlinear transient structural responses for complex structures will be described in Subsections 4.2 and 4.3, respectively.*

Finally, the following tabulation depicts the discussed problem-and-method categories:

Regime	Method	Type of Structure: Simple	Type of Structure: Complex
Linear	CLP	X	X
	FD	X	X
	FE	X	X
Nonlinear (Geometric and/or Material)	CLP	–	–
	FD	X	x
	FE	X	x
	CLP/Hybrid	x	X
	FE/Hybrid	x	X

X: Widely used
x: Occasionally used

* In Section 4, only representative references are cited on each main topic discussed; many more references pertinent to each topic exist, but no attempt is made here to be all inclusive in citing references.

4.2 CLP/Hybrid Approximate Methods

The method now known as the conventional lumped-parameter/hybrid method for predicting the nonlinear transient responses of complex built-up structures originated in the 1960's in connection with studies to predict the severe failure and postfailure responses of lifting-surface structures subjected to blast loading [36-41]. It was realized that sufficiently severe blast loading of typical complex built-up lifting surface structures could cause the structure to buckle at one or more spanwise stations during the transient response.

After buckle initiation, the structure tends to "fold" about that buckled station which remains at a fixed spanwise location. Also, after buckle initiation, the moment-carrying ability of the structure at that "buckled station" decreases as the postfailure deflection angle θ (see Figs. 4.1 and 4.2) increases, as one expects theoretically and confirms experimentally [36-47] from testing various simple as well as model and full-scale complex built-up structures. Unloading occurs along a "pseudo-elastic" straight line whose slope depends upon the maximum θ angle from which unloading occurs. This unloading slope decreases as θ_{max} increases.

Figure 4.3a is a schematic illustrating typical moment versus angular rotation behavior at a buckled station of a built-up beam structure, including unloading and reloading. If unloading is followed by reversed loading sufficient to produce buckling in that direction followed by continued reversed loading, unloading, and reloading, the associated typical moment vs. θ behavior is as depicted in Fig. 4.3b. Hence, if the structure is subjected to transient loads such that these types of behavior can arise, one must accommodate this type of behavior in a simulation model intended to predict this type of nonlinear response.

Figure 4.4 [45] depicts a cross-section of a 4-spar wing (beam). The static postfailure bending moment versus postfailure rotation angle θ behavior of a similar 3-spar wing is given in Fig. 4.5, together with predicted behavior from a simple conceptual model. The load-deflection characteristics of this 4-spar structure in the postfailure range with unloading, reversed loading, reversed failure, etc. are shown in Fig. 4.6 together with predicted behavior for this static-test example.

Similar experiments and analysis have been conducted on helicopter and/or general aviation aircraft structures and substructures [48-59] to evaluate the failure modes, failure loads, and postfailure load-deflection behavior of various components and structural assemblies of typical helicopters. Fuselage frames, landing gear structure, stroking seats, etc. have been studied both experimentally and analytically.

Similarly, typical automobile frames, body structure, and stiffening structure exhibit buckling and subsequent folding and crush-up behavior both in static-loading tests and in crash-impact tests [58-77]. Each of the many possible modes of initial "failure" and subsequent load-deformation behavior must be identified and accommodated properly in a prediction model in order to obtain realistic predictions of the nonlinear transient structural responses.

In the CLP/Hybrid method of analysis, the structure is represented by an assemblage of generalized masses connected by stiffness elements (extensional and/or bending) such as planar or 3-d beams [38, for example]. Typically the equations of motion representing this model are solved timewise numerically, while accounting for the applied loading arising from crash, impact, blast, etc. At each time instant, the stresses and/or load resultants are evaluated at many locations along the structure and compared with the critical value at that station (for incipient buckling, for example). If the evaluated value exceeds the critical value at that station, the computer program is instructed to account thereafter for the presence of a nonlinear hysteretic spring at that station; appropriate nonlinear load-deflection characteristics are assigned to that nonlinear spring. The timewise solution procedure continues, with additional nonlinear springs introduced at various other locations as the response and attendant criteria dictate. The calculation continues until structural rupture occurs at some station or the analyst decides to halt the calculation for some other reason.

The CLP/Hybrid method reported in Ref. 41 is an assumed-mode method which utilizes the natural-mode normal-mode equations of motion before buckling failure. Thereafter, these same normal modes are used together with a hinge mode introduced at the failure station; hence, the method becomes an assumed-mode method. This is a specialized analysis [41] which for the applicable structure is much more efficient computationally than the generalized-coordinate CLP/hybrid analyses [38].

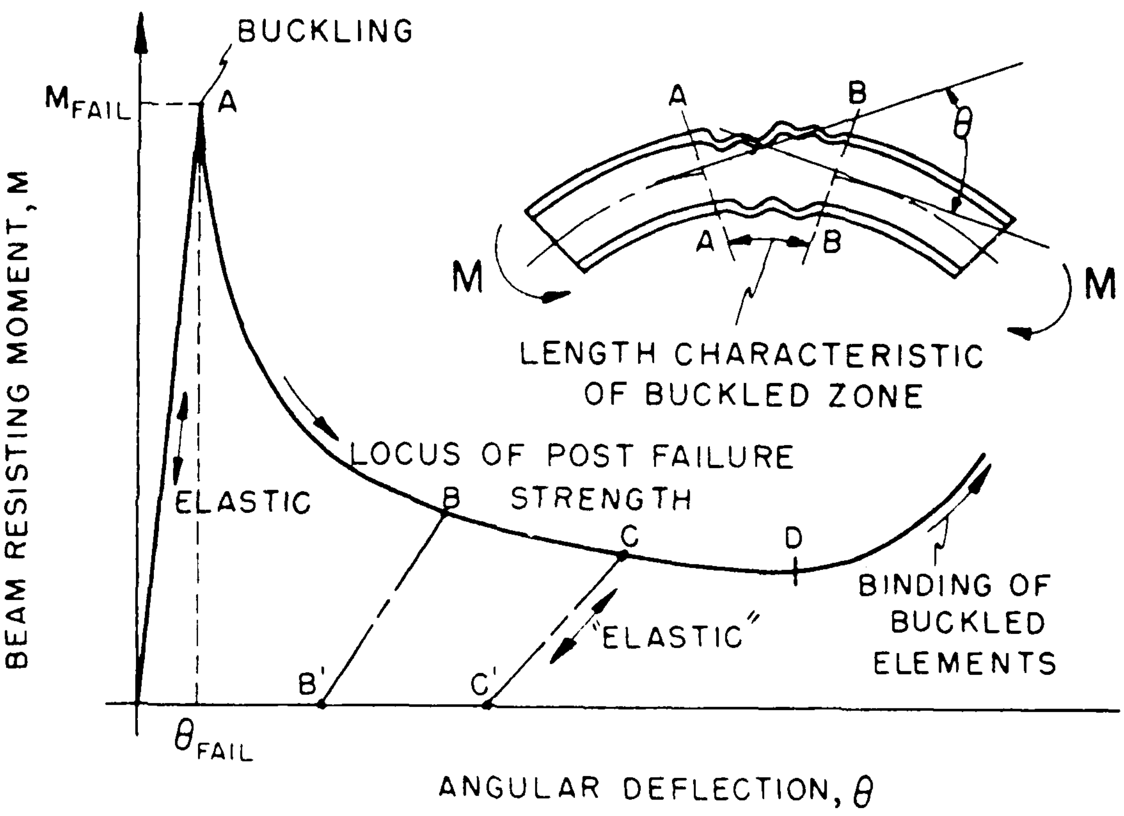
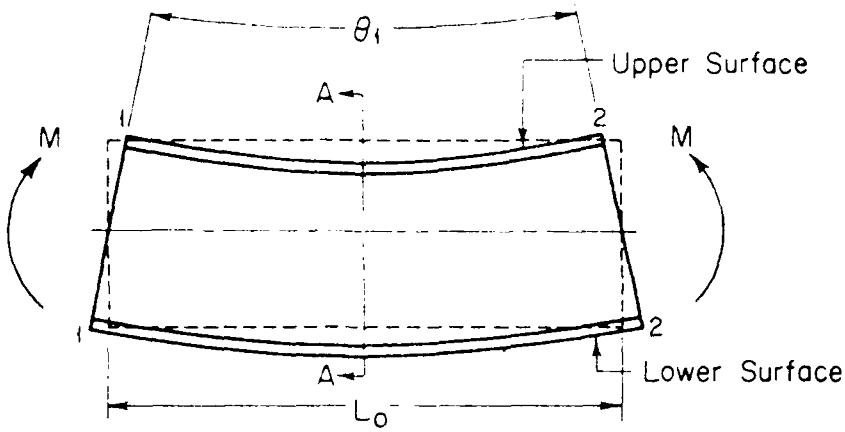
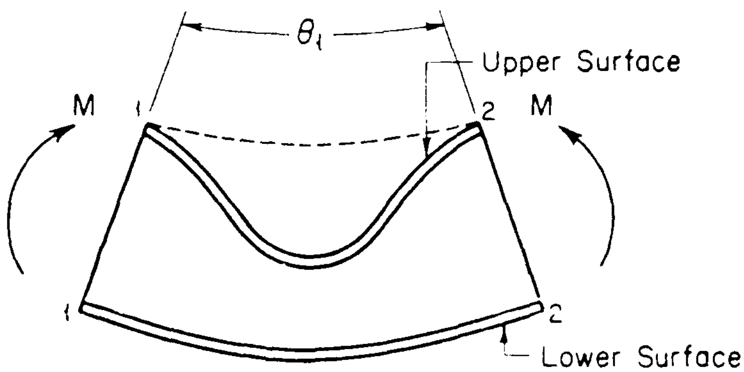


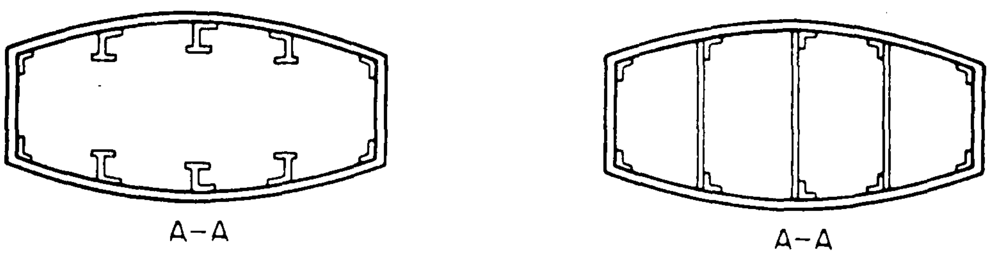
Fig. 4.1. Structural Behavior Typical of Built-Up Beams (Ref. 44)



(a) Before Failure



(b) After Failure of Upper Surface



(c) Typical Cross Sections of Shell Beam

Fig. 4.2. Segment of Shell Beam Under Pure Bending (Ref. 45)

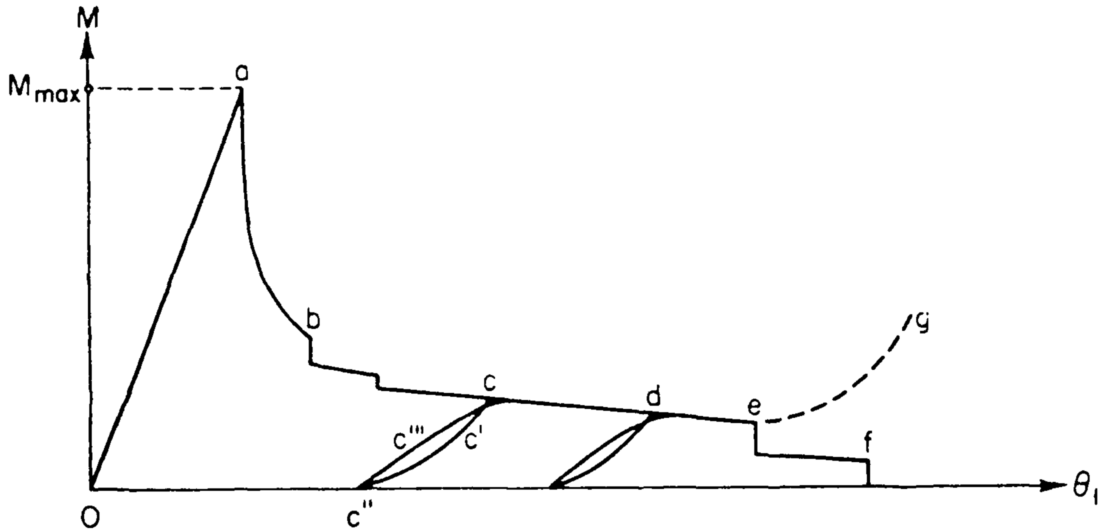


Fig. 4.3a. Basic Postfailure Structural Behavior of Built-Up Beams (Ref. 45)

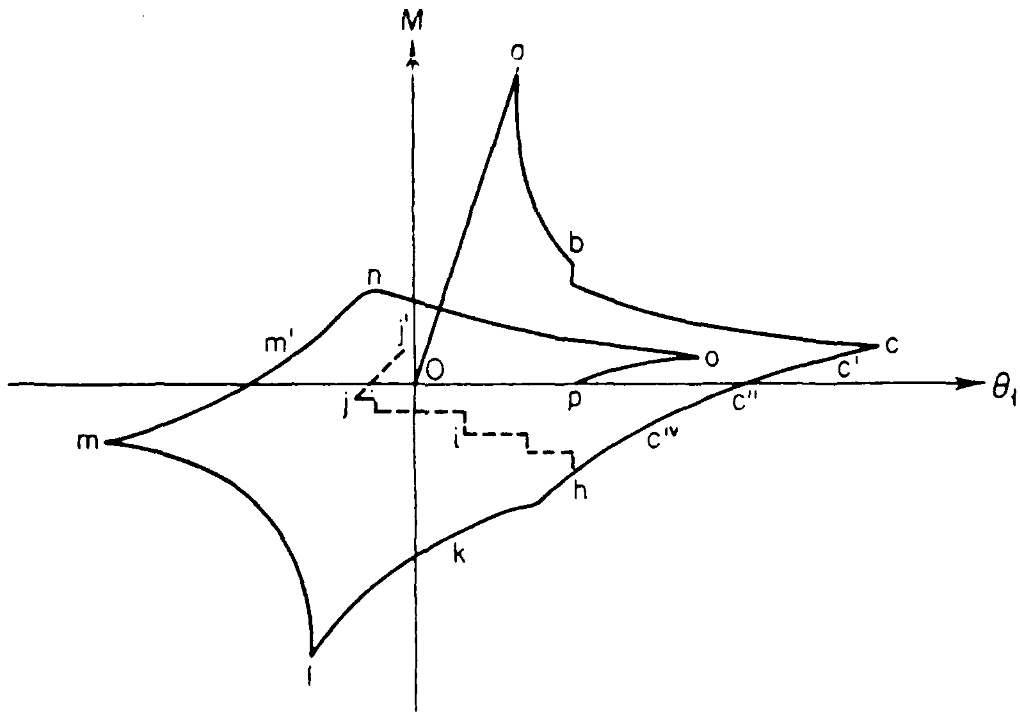


Fig. 4.3b. Additional Postfailure Loading Paths Possible for Built-Up Beams (Ref. 45)

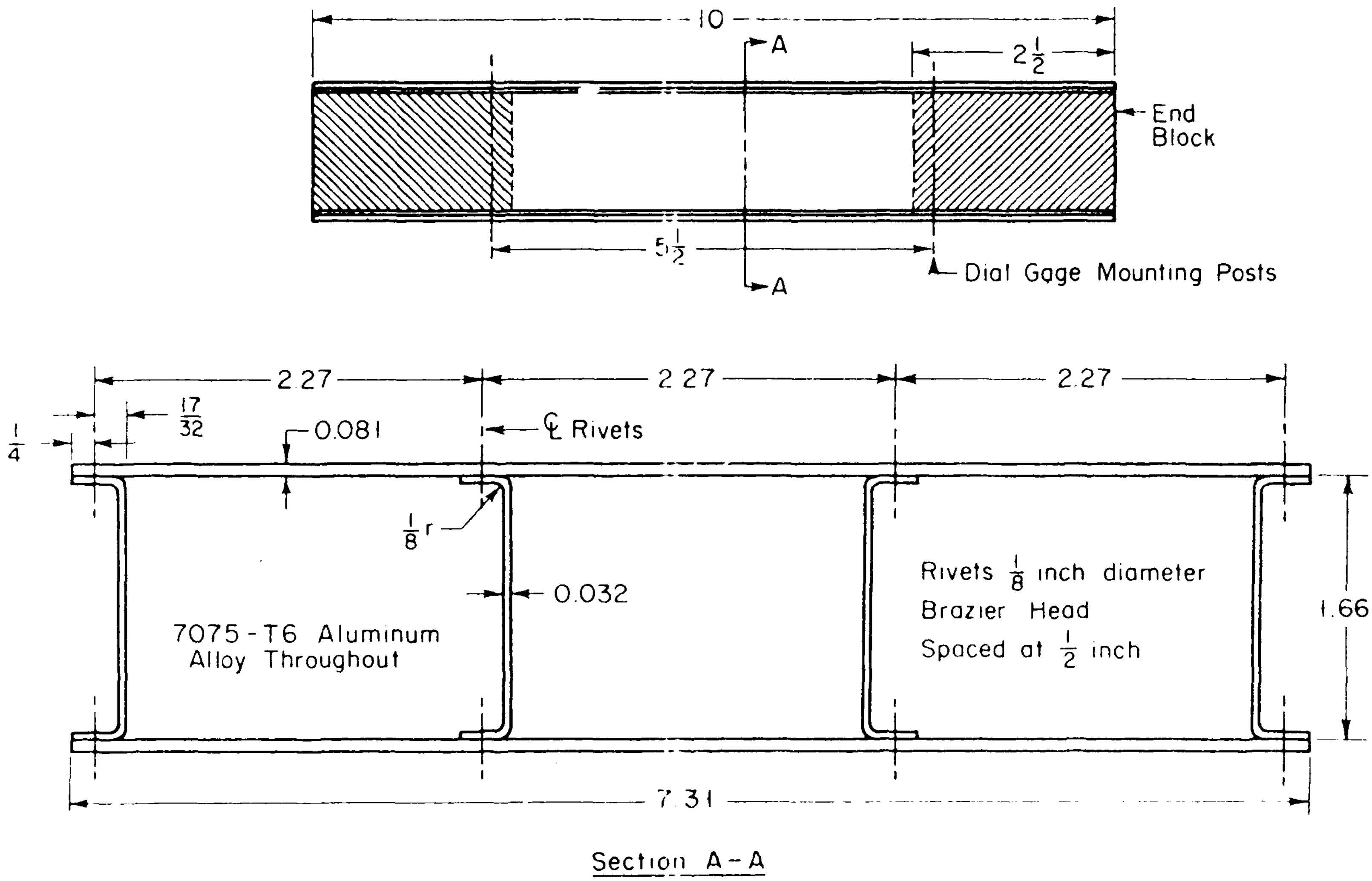


Fig. 4.4. Dimensions of Four-Spar Beam (Ref. 45)

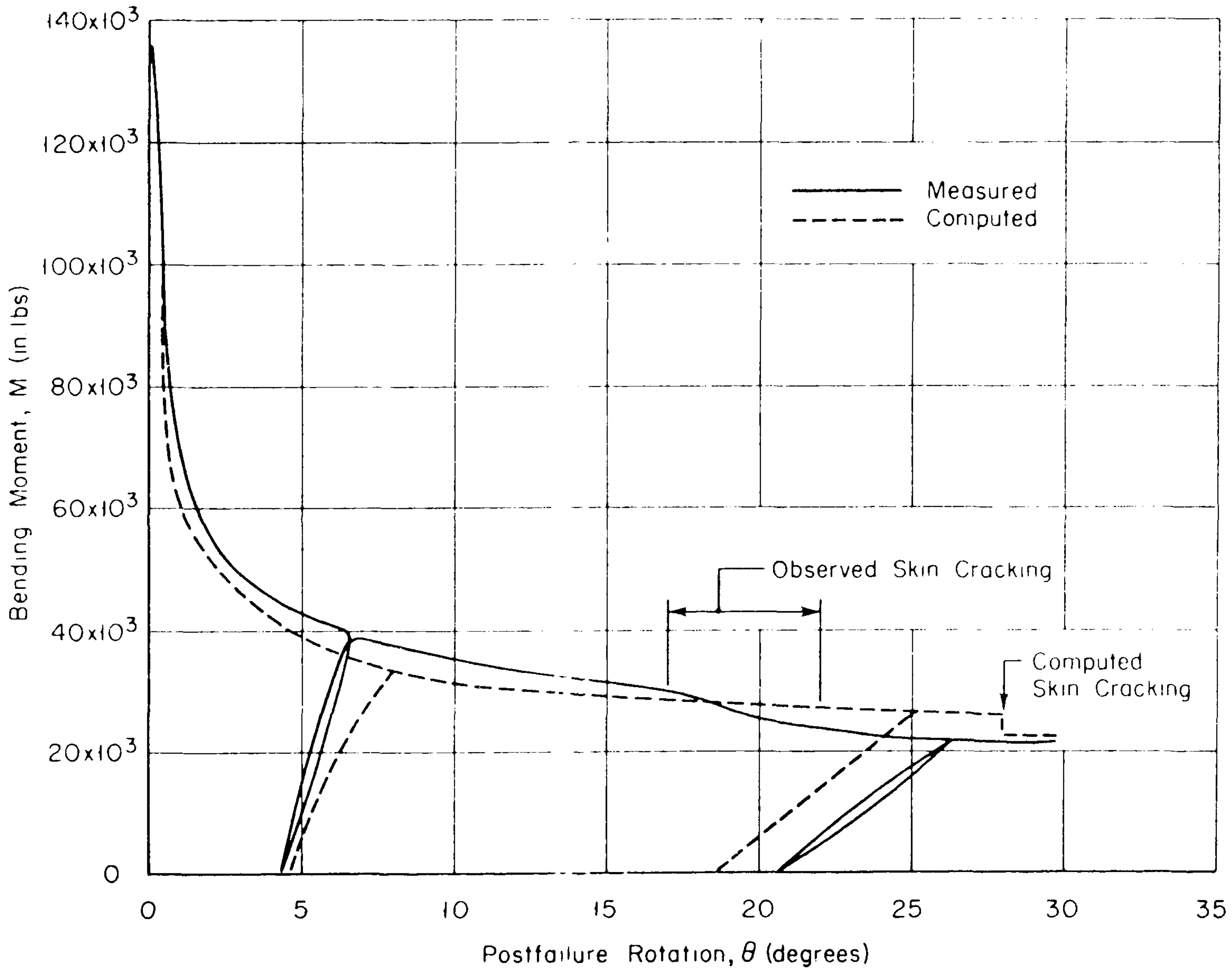


Fig. 4.5. Bending Moment versus Postfailure Rotation for A Three-Spar Beam (Ref. 45)

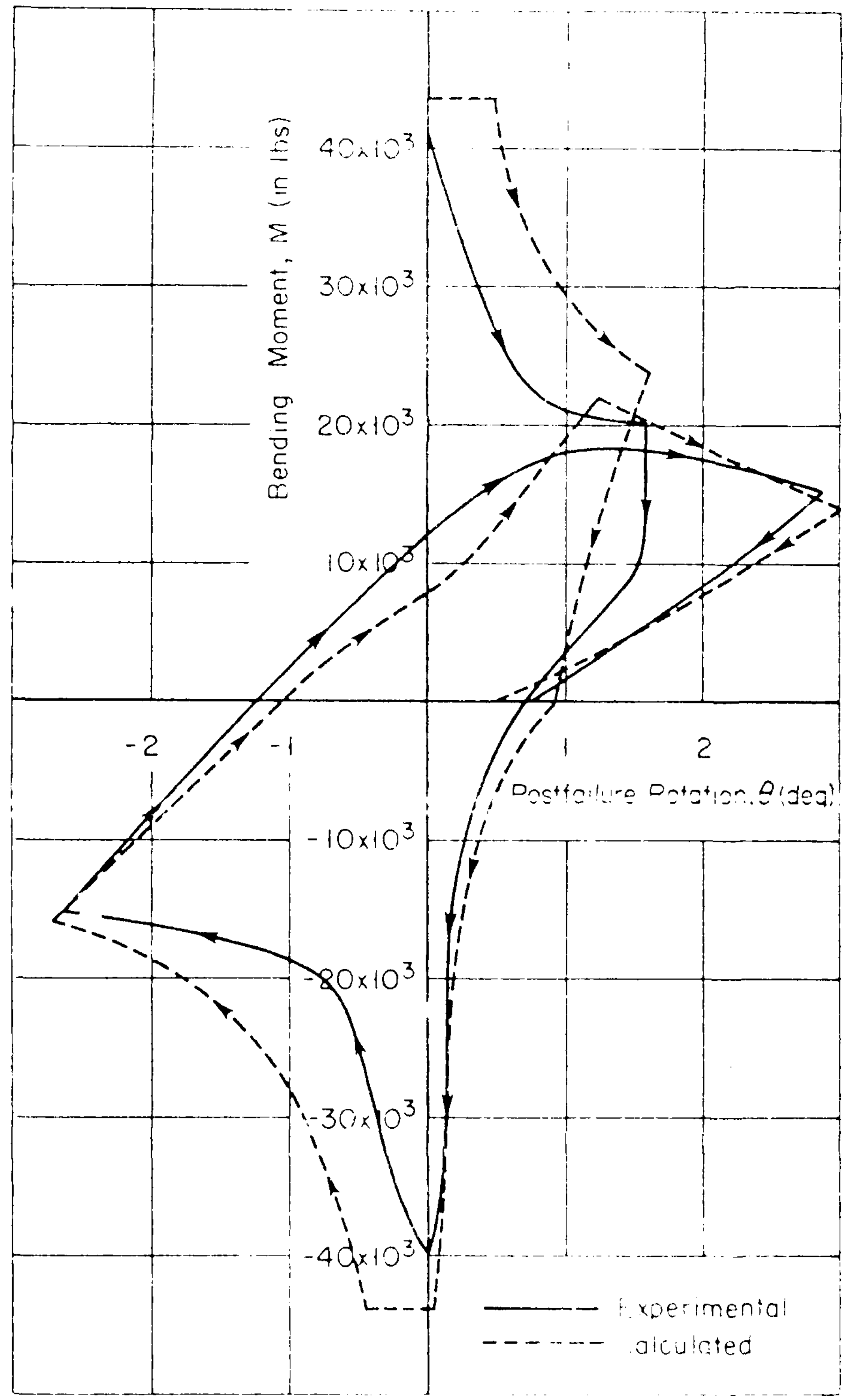
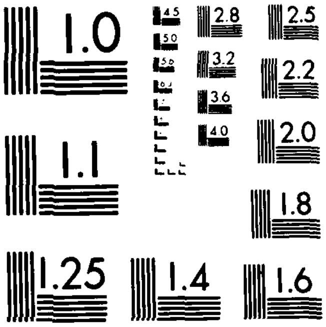


Fig. 4.6. Bending Moment versus Po[illegible] [illegible]
for Four-Spar Beam [illegible]

AD-A131 696 REVIEW OF AIRCRAFT CRASH STRUCTURAL RESPONSE RESEARCH 2/2
(U) MASSACHUSETTS INST OF TECH CAMBRIDGE AEROELASTIC
AND STRUCTUR.. E A WITMER ET AL. AUG 82 ASRL-TR-198-1
UNCLASSIFIED DOT/FAA/CT-82-152 F33615-77-C-5155 F/G 11/4 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

The load-deflection behavior of the generic nonlinear hysteretic spring may depend upon the current value of a measure of the deflection--such as, for example, the angle θ shown in Fig. 4.2 to represent the static moment versus angular rotation behavior at the "buckled station" of this example multi-spar wing structure [45]. The internal moment which can be carried there depends not only upon θ but also upon how that value of θ was reached; that is, whether that θ angle was reached by a monotonically-increasing path or by pseudo-elastic unloading from an earlier maximum value of θ, etc. (Figs. 4.5 and 4.6 depict schematically the types of hysteretic behavior that such models must be able to represent.)

In transient response problems, however, one must account for dynamic rather than just static conditions. In the present failure-postfailure context, dynamic effects may manifest themselves primarily in two ways. First, the incipient-buckling stress or incipient-buckling moment or buckling mode itself under dynamic conditions may differ from that observed under static conditions; this matter has been studied by various researchers for various types of simple and of complex built-up structures [78-83]. Second, the structural material comprising the "buckled zone" of the structure may be composed of material whose yield strength depends significantly upon the local strain rate; hence, the load-carrying ability at that structural station may depend upon both the deflection and the deflection rate (or strain rate).

Note that the internal structural generalized force of interest may be a moment and the associated measure of overall deflection may be an angular rotation θ of that buckled region. On the other hand, the "axial force resultant" F (rather than the moment) may be of interest and the associated measure of overall deflection of that buckled-folded region may be an axial displacement Δ. Thus, one may characterize these force dependencies by writing

$$M = M(\theta,\ \theta\,\text{path},\ \dot{\theta})$$
$$F = F(\Delta,\ \Delta\,\text{path},\ \dot{\Delta})$$

where $(\dot{\ })$ means the strain rate $d(\ )/dt$, where t denotes time.

While in principle one could carry out very detailed modeling of the structure in the "failure region" and could include a strain and strain-rate dependent description for the material throughout that region, practicality and expedience lead normally instead to the use of empirical test results to modify the static failure criteria and postfailure load-deflection behavior to account approximately for strain rate effects [77]. Some analysts neglect strain rate effects entirely because they believe that the practical fidelity of modeling employed is insufficient to warrant attempting to include strain-rate effects or because the strain-rate dependence of the material being employed is either unknown or believed to be small [39, 49].

For various types of ductile-metal built-up complex structures (multispar-skin, discretely-stiffened skin, honeycomb-stiffened skin, skin-stringer-frame, etc.) extensive static and/or dynamic tests have been conducted to measure their incipient-failure and postfailure load-deflection behavior [42-59, 75]. Simplified energy-based prediction methods have been developed and display generally very good agreement between predicted and measured static postfailure load-deflection behavior for essentially all configurations studied

[42-59, 75]. Thus, a considerable body of information has been generated to guide the analyst (who is seeking to analyze a built-up ductile-metal structure) in devising realistic and reliable approximations of the postfailure behavior at possible stations of interest of his structure; however, corresponding data for composite-material structures are relatively sparse. Carrying out a CLP/Hybrid analysis successfully requires the analyst to exercise skilled judgment and to call upon a significant background of experience on failure and postfailure behavior of complex built-up structures. In this problem area, the inexperienced analyst will encounter a considerable amount of difficulty and frustration.

It should be noted that the CLP/Hybrid approach can be applied to ductile-metal complex built-up structures or to composite-material structures. For each type of structure, one must provide for accommodating (a) the proper modes of incipient failure that can occur (and the associated incipient-failure criteria) and (b) appropriate descriptions of the postfailure load/deflection and/or load/deflection/deflection-rate behavior.

Also, the "hybrid" feature which represents the nonlinear hysteretic load/deflection/deflection-rate behavior of an automatically-selected "failed structural region" can be employed with equal facility with either:

(1) The Conventional Lumped Parameter Method

or

(2) The Finite-Element Modeling Method .

Accordingly, in Subsection 4.3 where the more detailed methods (FE and the FE/Hybrid methods) are discussed, a description of this Hybrid Feature is not repeated.

Numerous specialized limited-capability computer programs of the CLP/Hybrid type exist [48, 49, 68, 72, 74, 76, 82, 84-86]. For example, Catlin et al [48, 49] simulate the vertical impact of a helicopter fuselage by representing the structure by lumped masses connected by a preselected 2-d arrangement of nonlinear axial and rotational springs. The other cited programs pertain to portions of automobile structure simulating a crash situation; Kamal et al [74, 76, 77] developed the FEBIS program to simulate vehicle-to-barrier head-on impact wherein the vehicle is modeled by lumped masses interconnected by various nonlinear springs to represent the internal forces associated with the torque box, front frame and bumper system, drive-train, sheetmetal, firewall, radiator, engine mounts, and transmission mounts. Laboratory crush tests of these various components provide the nonlinear hysteretic spring data. The SCORES program by Fitzpatrick [86] is concerned with a 2-d model of an occupant which collides with the steering wheel, steering column, and knee-restraint system of an automobile in a head-on crash; here again the system is modeled by lumped masses with nonlinear hysteretic springs representing the load-deformation characteristics of the deformable structure. Prescribed are the crash input g-loads g(t) to the front of the occupant compartment; primary interest centers upon predicting the g-loads experienced at several locations on the occupant model.

Computer programs representative of the hybrid type but with a more extensive capability are those of Wittlin et al [52-57], McIvor et al [87], Shieh [88], and Young [89]. The KRASH program [52-57] is a lumped-parameter/hybrid simulation, while those of Refs. 87, 88, and 89 are of the finite-element/hybrid type. The UMVCS program [87] and the CRASH program [89] represent the structure by a 3-d array of rods and beams, with yielding and plastic-hinge behavior accommodated at the ends of these elements; test data are used to define the moment-rotation behavior at those hinges. Shieh's program [88] is similar but represents the structure by a 2-d array of beams, with plastic hinges permitted only at the ends.

Program KRASH [50-57] has undergone the most extensive development and application of any of these hybrid codes, and is generally considered to be the most convenient, useful, and comprehensive for use in preliminary and parametric design studies. In this program the structure is represented by point masses each with 6 degrees of freedom connected by an arbitrary 3-d array of beams. The effects of plastic behavior are taken into account through the use of nonlinear loading, unloading, reloading stiffness properties; those prescribed nonlinear spring properties are provided from crush tests and/or from supplementary analysis [50-57]. The KRASH program has been applied to the crash response analysis of helicopters [3, 90], general aviation aircraft [91], and locomotives [92], for example.

As summarized in Ref. 3 (pp 89-90), the capabilities available in KRASH are:

<u>Primary Features</u>

- Lumped mass representation.
- Nonlinear external spring and internal beam structural elements: the external springs represent nonlinear crushable structure, landing gear, soil, friction, and plowing reactions, while the internal beams represent airframe structure nonlinearities via stiffness reduction factors (KR), and, also, structure failure (rupture force or deflection) and damping.
- Large structure displacements and rotations.
- Three-dimensional impact simulations, model symmetry, sloped surface impact.
- Rigid elements via massless nodes.
- Automated occupant survival indicators: livable volume change, volume penetration by hazardous masses, Dynamic Response Index (DRI).
- Miscellaneous features, such as aerodynamic lift, angular moments as mass points, cross products of inertia, prescribed acceleration pulses at mass points.
- Restart.

<u>Output Information</u>

- Mass point response time histories (displacement, velocity, acceleration).
- Energy distribution:

  Mass - kinetic, potential
  Beam - strain, damping
  Spring - crushing, friction

- Beam element strain and damping forces, stresses, relative displacements, rupture summaries.
- Spring element loads and deflections.
- DRI response, cg velocity, volume change/penetration.
- Print and plot of responses, element data.
- Energy summaries.

These KRASH capabilities are summarized in slightly different terms on pp 1-2 of Ref. 57 as follows:

- Define the response of six degrees of freedom (DOF) at each representative location, including three translations and three rotations.
- Determine mass accelerations, velocities, and displacements and internal member loads and deformations at each time interval.
- Provide for general nonlinear stiffness properties in the plastic regime, including different types of load-limiting devices, and determine the amount of permanent deformation.
- Define how and when rupture of an element takes place and redistribute the loading over the structural elements involved.
- Define mass penetration into an occupiable volume.
- Define the volume change due to structural deformations of an occupiable volume.
- Provide for ground contact by external structure including sliding friction and a nonrigid ground surface.
- Include internal structural damping.
- Include a measure of injury potential to the occupants; for instance, the probability of spinal injury indicated by the Dynamic Response Index (DRI).
- Determine the distribution of kinetic and potential energy by mass item, the distribution of strain and damping energy by beam element, and the crushing and sliding friction energy associated with each external spring.
- Determine the vehicle response to an initial condition that includes linear and angular velocity about three axes and any arbitrary vehicle attitude and position.
- Provide a measure of the airplane cg velocity by means of translational momentum relationships.
- Analyze an impact into a horizontal ground and/or an inclined slope.
- Provide a measure of the internal stress state of internal beam elements.
- Analyze a mathematical model containing up to 80 masses and 150 internal beam elements.
- Treat up to 180 nonlinear element degrees-of-freedom.

The structural modeling provided by KRASH is quite realistic for aircraft frames and trusses but modeling of skin panels, sandwich panels, or composite-material panels can be done <u>only roughly</u> and requires the exercise of considerable engineering judgment and experience. The nonlinear internal or external springs which represent the failure and postfailure behavior of built-up metallic or composite-material beams under 1-d (not combined) loadings requires either pertinent experimental data or independent model estimates of these properties such as found in Refs. 48 or 3, for example. Thus KRASH can represent many of the main features present in the crash responses of vehicles of conventional and of composite-material construction. Because of the limited fidelity of structural and material modeling available, KRASH can be expected to provide useful overall crash response data, but fine-detail transient response data of high accuracy is beyond the capability of program KRASH. Hence, KRASH is versatile and highly useful, but must be applied for appropriate purposes and expectations. To be productive in meaningful engineering design and screening studies, KRASH must be applied by an analyst who has the experience and judgment to construct a structural/material model which contains the principal features of importance in crash-impact situations. The likely modes or patterns of incipient failure and associated failure criteria as well as the patterns of subsequent progressive failure and the associated load-carrying ability must be anticipated realistically; the simulation model then must be constructed so as to accommodate and represent this behavior. In this regard, the analyst is advised to become thoroughly familiar with the wealth of information and experience contained in Refs. 3, 48-58, and 90-92.

4.3 More Detailed Methods

Many analyses and computer codes have been developed (and much additional work is in progress) to represent simple and complex structures by a much more detailed model so that the many types of transient structural response, failure, and postfailure behavior present in a given structure can be accommodated faithfully and automatically--rather than crudely and by built-in rough preselected limited failure-postfailure models. Some progress has been made toward this goal; detailed modeling of limited categories of structures can be accomplished, but there are many types of modern composite built-up structures for which detailed rational models to represent nonlinear transient response behavior are not yet available.

From time to time surveys and compilations of structural analyses and computer code capabilities have been made; for example, Pilkey et al [93], Kamat [94], Belytschko [95], Chang and Padovan [96], Armen and Pifko [97], and Noor [98]. Both spatial finite-element and spatial finite-difference computer codes of widely-varying capabilities are available. Of particular interest here are those which accommodate geometrically- and materially-nonlinear <u>transient</u> structural response behavior; Ref. 98 cites 20 such computer programs;

ADINA	DANUTA	HONDO-II	NEPSAP	STAGSC-1
ANSR-I	DIAL	LARSTRAN-80	SAMCEF	STRAW
ANSR-II	DRAIN-2D	MARC	SAMSON	WECAN
ANSYS	DYCAST	MSC/NASTRAN	SESAM-69	WHAMS

---and there are many more. Recently Fong [99] reported an evaluation of 8 general-purpose finite-element computer programs:

ABAQUS	COSMIC/NASTRAN	MSC/NASTRAN
ADINA	EASE2	STARDYNE
ANSYS	MARC	

---only 4 of which (ANSYS, ABAQUS, ADINA, and MARC) have operational nonlinear geometric-material transient response prediction capabilities, including restricted classes of impact problems. See Refs. 98 and/or 99 (and/or also Refs. 51 and 93-97) for a tabulation of the various features and capabilities of these computer programs.

Certain of these computer codes have been written to analyze impact-crash responses of certain categories of structures. The most comprehensive and versatile of these programs is the finite-element program DYCAST [101-104] developed by the Grumman Aerospace Corporation under Grumman, NASA, and FAA sponsorship. Another similar computer program with more limited capability is ACTION [105, 106], which is also a finite-element program. For the categories of structures which each of these codes can model, the transient response including incipient-buckling, yielding, plastic behavior, etc. is accounted for automatically; no prescribed internal failure initiation and no prescribed internal postfailure hybrid-type load-deflection behavior is injected. An example of the application of DYCAST and ACTION (and of KRASH) to the analysis of and comparison with experimental data for a fuselage section impacted in a drop test is given in Ref. 91. Demonstrated is good overall transient response agreement between experiment and the predictions of KRASH, ACTION, and DYCAST but the superior modeling fidelity of the DYCAST code produced distinctly better detailed predictions and comparisons with experiment, as expected.

DYCAST has also been applied by Carden and Hayduk [107] to the analysis of the drop-test impact responses of various aircraft fuselage load-limiting subfloor structural concepts. A representative fuselage floor and subfloor sections with simulated attached "seats and passengers" was drop tested for each of several concepts. Accelerometers provided acceleration time histories at various locations on the specimen. High speed photographic measurements provided deflection data. Static load-deflection tests on each subfloor configuration provided data which were used in DYCAST to represent this subfloor behavior by nonlinear springs. Generally good experimental-theoretical agreement was found. However, in some instances the static failure patterns differed somewhat from those observed in the dynamic tests. This is suspected to be one of the principal reasons for the theoretical-experimental discrepancies noted. Also, no strain-rate dependent material effects were included in the analysis. The experiments conducted demonstrated the effectiveness of several very attractive load-limiting concepts for fuselage subfloor structure.

For detailed crash response analysis and design, it appears that the DYCAST program provides an excellent extensive baseline modular capability to which future needed features could be added effectively. This might include, for example, elements to represent various structural elements and composite-material layups, as well as appropriate descriptions for failure criteria and postfailure behavior of these items.

For convenient reference, the major features of DYCAST are quoted verbatim from pages 105-107 of Ref. 3, as follows:

- Nonlinear spring, stringer, beam, and orthotropic thin sheet elements.
- Plasticity.
- Very large deformations.

- Variable problem size.
- Restart (stop, review, and continue).
- Deletion of failed members.
- Four different numerical solution methods, three with internally varied time steps.
- Modular formulation.

The basic element library of stringers (axial stiffness only), beams (axial, two shears, torsion, and two bending stiffnesses), and orthotropic membrane skin triangles (in-plane normal and shear stiffnesses) allows the convenient modeling of aircraft-type structures built up from such components. The non-linear spring element is a general-purpose axial stiffness unit with a user-specified force-displacement curve.

The changing stiffnesses in the structure are accounted for by plasticity (material nonlinearity) and very large deflections (geometric nonlinearities). The plasticity enters the model through the nonlinear stress-strain curve for each element. The geometric nonlinearities are modeled by reforming the structure into its new shape after small time increments, while accumulating deformations, strains, stresses, and forces. In this way, the progressive crushing and folding of structural elements can be followed. The nonlinearities due to combined loadings (such as beam-column effects) are maintained, and the stiffness of the elements can vary depending on the combination of loads imposed on them.

The restart feature allows for a large problem, or one of long event duration, to be run in small time sequences. This minimizes the tie-up of computer facilities, allows the user to examine the response as it progresses, permits the ending of a simulation if a critical damage occurs, or permits the deletion of elements that appear to have failed as indicated by the stress and strain output.

The numerical time-integrators available are fixed-step central difference, modified Adams, Newmark Beta, and Wilson Theta. The last three have variable time steps, controlled internally by a solution convergence error measurement. Thus, the time steps increase and decrease as required during the simulation.

The modular formulation allows for easier addition of new elements, material types, time-integrations, etc. by structuring the program in well-defined modules with a minimum of interfaces with other modules.

The overall accuracy and computational cost of the simulation will depend on the quantity of elements used (fineness of the geometric model). The finer the model, the greater the accuracy and cost.

A user-oriented input/output format is utilized. The primary input data groups are:

- Numerical controls and options.
- Geometry (nodes and elements).
- Motion constraints (and impact surface).

- Initial conditions.
- Rigid masses.
- Material properties.
- Element cross-section geometries.
- Applied dynamic loads (if any).

The output data are in the form of:

- Printed displacement, velocities, accelerations, strains, stresses, and forces.
- Plotted histories of displacement, velocity, and acceleration at chosen nodes.
- Time-sequenced drawings of deforming structure or portions from any viewing angle.

This ends the verbatim quotation from pages 105-107 of Ref. 3.

It should be noted that although DYCAST models the (interior) structure in detail with finite elements which accommodate nonlinear geometric and material behavior, it also provides for accounting for nonlinear support or attachment structure by the use of nonlinear hysteretic springs whose mechanical properties must be prescribed by the user (from supplementary tests and/or analyses). In this sense, DYCAST also contains a hybrid capability.

To date the documentation found in the open literature for DYCAST is rather sparse [3, 103, 104]. Perhaps this is because DYCAST is regarded as a modular addition to PLANS (for static loading) which is documented in Refs. 101 and 102. However, it is hoped that similar comprehensive documentation for the nonlinear transient response program DYCAST will be provided soon to enable other researchers to use DYCAST, to appreciate fully its current capabilities, and to add further modules to extend its capabilities in useful directions. For example, although DYCAST has orthotropic plate elements including the Mises-Hill yield criterion, the Drucker flow rule, and Prager-Ziegler kinematic hardening [100], it may be useful to consider adding the present (or a modification of the) orthotropic elastic-plastic panel elements of the BR-1FC code of Ref. 108 which has been applied successfully to the blast response analysis of composite panel structures [109]. Also, it may be effective to consider the use of Quasi-Newton iteration methods for the implicit-time-operator solution of the nonlinear equations of motion in DYCAST, as discussed, for example, in Ref. 110. In this regard Bathe and Cimento [111] have shown by application of the ADINA code that the Broyden-Fletcher-Goldfarb-Shanno (BFGS) scheme (one of the Quasi-Newton methods) is particularly effective for the nonlinear transient response solution of the equations of motion by using implicit timewise finite difference operators.

SECTION 5

CRASH RESPONSE RESEARCH NEEDED

General comments on crash response research conducted during the past two decades are given in Subsection 5.1. Needed crash response research is discussed in Subsection 5.2, noting the general goals, the need for crashworthy airframe structures, and related crash response work -- much as described by Cronkhite et al [3] in USARTL-TR-79-11; the roles of laboratory test and full-scale tests are also noted. Ongoing and planned crash-response research of both general and helicopter related applicability is outlined succintly in Subsection 5.3. Crash-response research focussed on transport aircraft is indicated in Subsection 5.4 together with comments on a planned full-scale crash test. Finally, some comments on the roles of specimen level, subscale, and full-scale structural tests are offered in Subsection 5.5.

5.1 Comments on Procedures of Past and Planned Research

As pointed out by Thomson and Caiafa [2], very significant progress has been made in the past two decades in improving the state of knowledge of crash response and factors affecting the crashworthiness of aircraft and helicopters (as well as automobiles).

This progress has been achieved through the efforts of the U.S. Army, FAA, NASA, DOT, their numerous contractors. Static testing, impact testing, and crash testing of a succession of structural components, substructures, and structural assemblies has led to an understanding of the modes of failure and of the postfailure structural behavior (load-deflection, energy absorption, etc.) of various types of built-up metallic structures. Effective combinations and arrangements of structural materials and components were identified. Concurrent and subsequent full-scale crash testing of helicopters and aircraft served to provide confirming failure mode and detailed postfailure transient response data which could serve as "proof data" against which theoretical transient response prediction methods could be checked, and subsequently revised to remedy noted deficiencies.

Going hand-in-hand with this experimental work were efforts to develop reliable methods for predicting the failure modes and loads of each of the principal types of structural components involved, as well as their post-failure load-deflection and energy-absorbing behavior. The experimental observations were extremely important in guiding and channeling this theoretical effort along productive lines. Experimental failure and postfailure structural data enabled the analysts to devise effective and appropriate theoretical models of the structure to minimize the computational effort while accounting for the salient behavioral features of the structure. Consequently, theoretical methods have been developed for predicting successfully the non-linear transient responses of severely loaded structures for crashworthiness response purposes.

This type of integrated theoretical-experimental procedure has been followed by the U.S. Army, FAA, NASA, DOT, and associated investigators in the case of built-up metallic structures and in the more recent work on structures composed of composite materials [2,3,11]. In this newer category of structural materials and construction, the diversity of structural materials, arrangements, attachments, etc. is much more extensive than in the past. Hence, considerable effort will be required to identify the most effective and practical combinations of materials, layups, and structural concepts to achieve acceptable crashworthy design; progress in this direction has been made as reported by Cronkhite et al [3], Thomson and Goetz [11], Thomson and Caiafa [2], Carden and Hayduk [107], and in the studies leading to the U.S. Army Crash Survival Design Guide [13-17]. Much more work along these lines will be needed to assess the comparative effectiveness and practicality of the numerous candidate materials and structural concepts [112,113]; this will be an evolutionary process.

The overall structural crashworthiness research plan outlined in Refs. 1, 2, 113, and 114 appears to represent a logical and orderly succession of investigations judiciously combining experiment and analysis. Recommended are static and impact tests on a succession of laminates, structural elements (beams, frames, etc.), and substructure configurations such as fuselage floors, fuselage shell with floor, wing box structure, etc. Skins of graphite/epoxy, glass/epoxy, Kevlar/epoxy or hybrid combinations of these materials in cloth (or unidirectional ply form) are to be studied together with these materials used as facings on various types of honeycomb sandwich beams and frames. Also, concepts utilizing discrete longitudinal and/or circumferential stiffeners of composite material are to be studied. Various joint concepts need to be assessed in this crash response context. These tests are intended to assess the energy absorption, failure, and postfailure behavior of these various configurations and materials, under both static and crash loading conditions. Laboratory scale models and tests (static and dynamic) are to be followed by subsequent tests on large-scale components which simulate closely real-scale fabrication; these may be regarded as proof-of-concept or final-validation tests.

5.2 Needed Crash Response Research

The crash response research which is needed to develop better crashworthy designs for aircraft has been described clearly and concisely by Cronkhite et al [3], Thomson and Goetz [11], and Thomson and Caiafa [2]; those observations still apply and are largely paraphrased in Subsections 5.2.1, 5.2.2 and 5.2.3. The roles of element and subscale laboratory experiments and tests of full-scale structures are noted in Subsections 5.2.4 and 5.2.5, respectively.

5.2.1 General Goals

As described in Ref. 2, the general goals of (a) crash response research and (b) the use of advanced composite materials to achieve crashworthiness performance equal to or better than achieved with conventional built-up metallic configurations are as follows:

O Crash response performance of aircraft (a) of conventional metal construction and (b) of composite-material construction both designed to the same basic requirements need to be measured and assessed in order to draw upon the extensive accumulated experience on crash performance of metallic structures. Such comparisons are needed to permit assessing how well composite structures fare in meeting crash requirements which have been developed and based on experience with metallic structures.

- O Seek improved crashworthy design concepts which serve as part of the primary load-carrying structure under normal conditions and absorb energy effectively in a crash. Effective performance with a minimum weight penalty is desired.

- O A program of study which provides a systematic and growing body of knowledge and experience on aircraft crash response is needed. This research should build from the material-coupon level to the structural element level, to small structure assemblages with i its and cutouts, to structural assemblages with skins, frames, stiff rs, and attachments, and to "complete" airframes. An integrated ram of tests, analyses, and design studies should be carried out each stage.

- O Design information on the characteristics of candid mposite materials and of structural elements composed of con ations of composite and/or honeycomb materials need to be developed further. Failure loads, failure modes and mechanisms, and energy-absorption characteristics of these items need to be determined by systematic testing and analysis to assess their behavior in a crash environment. Crash environmental conditions pertinent to transport, general aviation aircraft, and helicopters must be included.

- O Analysis and design tools in the form of computer programs for several levels of detail and for various portions of the system are needed.

- O Accumulated crash response experience may lead in turn to revised crashworthiness requirements.

5.2.2 Crashworthy Airframe Structures

To develop crashworthy composite-material airframe structures, information needs to be developed further in the following areas [3,114]:

- O Composite-material behavior under static and crash conditions (coupon level and structural element level)

  - + Failure modes and mechanisms

  - + Structural integrity after incipient failure

  - + Postfailure load-deflection and energy-absorption behavior

  - + Abrasion and tearing behavior of skins

  - + Crushing behavior of cores and honeycomb sandwich concepts

+ Strain rate and temperature effects on failure modes and postfailure behavior

0 Testing and evaluation of joints, hardpoints, and cutouts to determine their strengths and failure modes, including their behavior under dynamic crash conditions.

0 Develop analysis tools on several levels for composite-material structures.

  + Analysis of structural elements (will require and be guided by observations and measurements in each of various categories of element-level experiments).

  + Analysis of aircraft-type structural assemblies (portions of the entire aircraft) -- experimental static and dynamic data are needed to guide the development of necessary analysis modules which could be added to the appropriate computer code DYCAST and to validate DYCAST prediction capabilities.

  + Gross analysis of the overall aircraft system, including the landing gear, fuselage-wing airframe, and seat/restraint system (KRASH, DYCAST, and/or DYSOM could be applied but each requires further validation)

0 Investigate crashworthy concepts for possible integration into future designs

  + Sandwich stiffeners with honeycomb cone with Kevlar or hybrid facings

  + Graphite-epoxy and hybrid frames

  + Energy absorbing load-limiting subfloors (Carden and Hayduk [107])

  + Crack stopping arrangements and attachments of structural elements

5.2.3 Related Areas

Some additional problem areas needing study in the crashworthiness context for general aviation and transport aircraft are [3,11,114]:

0 Interaction of the landing gear and loads with the composite airframe structure. Load transfers, failure mechanisms, and failure sequence needs to be investigated for typical crash scenarios. Appropriate attachment and load-transfer structural concepts should be analyzed and evaluated by impact and typical crash test conditions.

0 Energy absorbing seat/restraint concepts should be evaluated in conjunction with composite-material structures to which these are attached at various representative locations along the fuselage. Impact tests under typical crash conditions should be conducted to assess the overall effectiveness of the seat/airframe-structure combination.

o Concepts to enhance fuel tank integrity in the wing and fuselage of composite-material aircraft structures (but beyond the intended scope of this review).

5.2.4 Laboratory Tests

The great variety and complexity of candidate composite materials and of structural arrangements and layups requires careful and systematic laboratory testing to determine the mechanical-structural behavior of composite-material structural elements and structural assemblages. Each combination of composite materials, structural arrangement, and loading condition can lead to any one of several modes of incipient failure: matrix rupture, debonding, delamination, fiber rupture, buckling,....

Static tests of structural elements (of each type) are necessary to determine the incipient-failure, postfailure, and energy absorption behavior. For a given type of structural element, some composite materials soon lose their structural integrity after incipient failure, but other composite materials exhibit a much higher retention of structural integrity until very extreme structural deflections have accrued. Systematic static experiments are essential to explore and verify this behavior; this provides essential baseline information. However, under dynamic test conditions, somewhat to very different failure modes and postfailure behavior might occur.

Since important dynamic effects on incipient failure and postfailure structural behavior might occur, it is important to conduct careful well-controlled laboratory type tests to evaluate this behavior for an appropriate range of strain-rate and loading conditions. Tension or compression or combined loading conditions could be used to study composite material behavior under dynamic conditions at the material-coupon level; this type of information would contribute to a better understanding of the basic behavior of composite materials under dynamic conditions. However, for design purposes it may be more effective and efficient to explore this behavior at the structural element level (cylindrical tube, built-up I-beam, sandwich beam, frame,...). Thus, it is recommended that element level (a) static tests and (b) dynamic-impact tests be conducted and analyzed to assess similarities and differences in failure modes and loads as well as differences between the actual transient response behavior and that predicted by assuming that the static mechanical behavior data applies also to the dynamic situation. Such comparisons could lead to the determination of dynamic modification factors which could subsequently be used tentatively in the design process, as done by the automobile crashworthiness community [77, for example]; such "corrections" if needed are expected to have a narrow range of applicability. Such factors could be applied to modify static-property DYCAST calculations in element-level (or substructure-level) design studies.

Similar static tests, impact tests, and comparisons would be useful also when applied to structural assemblies (portions of the fuselage skin, frames, keelson, subfloor, floor, and seat/restraint system or to small assemblages). Basic transient behavioral data would be generated for its inherent value and to serve the purpose of evaluating, validating, and improving DYCAST prediction capabilities for future applications.

The cited laboratory-scale (subscale) static and dynamic experiments on the various composite-material and structural concepts will be valuable for identifying the principal modes of failure under crash conditions, and will be useful for "suggesting" effective modeling simplifications. These simplified models are expected to focus on and emphasize the principal types of behavior involved withou including burdensome unnecessary detail. Such models will accommodate the pertinent incipient-failure criteria such as buckling, delamination, debonding, tear, etc. Appropriate material characterization information (stiffness, strength, inelastic behavior,...) will need to be supplied for each particular material/layup system.

5.2.5 Full-Scale Tests

Full-scale static and crash-response tests play an essential role in confirming the validity of the design of the aircraft and perhaps in uncovering certain full-scale structural behavior that earlier subscale structural tests had not revealed. Data from such tests provide additional information to validate and upgrade analysis/design procedures and computer codes. However, a full-scale crash response test is very expensive and permits one to study the response of the system to only one condition of the many crash conditions of practical interest.

In contrast with crash tests of full-scale general aviation aircraft where a limited number of seats and occupants is involved, crash response testing of transport aircraft provides the opportunity to investigate and compare the performance of a variety of seat and restraint systems at various stations along the fuselage, thereby, including a range of impact conditions. Many photographic, strain, displacement, acceleration, and load measurements are needed to extract maximum benefit from such an opportunity. This will require careful design, planning, and instrumentation -- as is currently being done by FAA/NASA, for example, in preparing for a full-scale crash test of a B-720 aircraft [2].

5.2.6 Comments on the Roles of Element, Subscale, and Full-Scale Crash-Impact Tests

The extreme expense involved in carrying out a full-scale crash test, and the fact that only one impact condition of one of many important crash scenarios possible can be explored in a single test, requires the investigator to carry out nearly all of the experimental basic data and assessment work on laboratory type subscale structural models for both static and dynamic purposes. In this context, one can develop a high degree of understanding of nonlinear crash response behavior and can develop and validate both theoretical transient response prediction methods and crashworthy materials/structures concepts. Still needed, however, are a small number of full-scale tests to provide data to validate these transient response methods in detail for full-scale conditions to give one a clear level of confidence in the reliability/adequacy of such prediction methods for design use. These prediction methods (like KRASH and DYCAST, for example), in turn, can be used for preliminary design studies encompassing a reasonably wide range of conditions. Drawing upon such calculations, laboratory tests, background information from the Crash Survival Design Guide, etc., the designer should be able to develop a design which meets reasonable crashworthiness standards, but this is an area in which a succession of developments and improvements can be expected, given the appropriate level of government and industry support and cooperation.

5.3 Current Basic and Helicopter-Related Research

The report USARTL-TR-79-11 by Cronkhite et al [3] has documented the state of designs, experiments, and analysis methods for dealing with the crash-impact characteristics of advanced airframe structures, including an extensive period of pioneering work by the U.S. Army Research and Technology Laboratories (AVRADCOM) and its contractors.

Subsequent to (or in parallel with) the Ref. 3 report, there have been at least four research efforts designed to extend the information base on crash response of advanced-composite structures. These four programs are sketched in key-word outline form in the following under the headings [113, 114,115]:

A. Extension of Work Reported in USARTL-TR-79-11 by Bell Helicopter Textron under AVRADCOM.

B. Development of Data Base on Composite Materials/Structures with Emphasis on Helicopter Applications (AVRADCOM at NASA-Langley Process/Application Branch, Materials Division)

C. Extension of Data Base Studies (AVRADCOM/NASA/Bell)

D. Advanced Composite Airframe Program (Bell Helicopter Textron and Sikorsky Aircraft under AVRADCOM)

A. Extension of Work Reported in USARTL-TR-79-11 by Bell Helicopter Textron under AVRADCOM

- 0 Failure and Postfailure Behavior of Helicopter Fuselage Components
- 0 Subfloor Concepts: Various Sandwich-Composites
- 0 Graphite-Epoxy Sandwich
- 0 Kevlar-Epoxy Sandwich
- 0 Small Structural Components
  - + Static Tests, Impact-Drop Tests
  - + Impact Response
    - o Graphite-Epoxy Readily Loses Structural Integrity
    - o Kevlar-Epoxy: Superior Retention of Structural Integrity
- 0 Full-Scale Fuselage Sections: Frame, Skin, Subfloor
  - + Drop-Impact Tests of Two Specimens

+ Transient Response Data Obtained, Analyzed, and Correlated with Predictions

0 Report Release is Imminent (by Bell Helicopter Textron and AVRADCOM)

B. Development of Data Base on Composite Materials/Structures with Emphasis on Helicopter Applications
(AVRADCOM at NASA-Langley Process/Applications Branch of the Materials Division)

0 Tube and Beam Configurations

+ Failure Modes and Postfailure Behavior

+ Energy Absorption Characteristics

+ Crush Characteristics

+ Assess Structural Integrity from Incipient Failure to Loss of Load-Carrying Ability

0 Composite Subfloor Concepts

+ Design to Same Specifications as Metallic Designs Tested by Carden and Hayduk of NASA-Langley

+ Static Tests for Failure Modes and Load-Deflection Behavior

+ Impact Tests for Failure Modes and Transient Crush Behavior

+ Compare Composites Designs with Behavior of Previous NASA-Langley Metallic and Composite Designs

0 Helicopters: Steep-Descent Impacts are Dominant

C. Extension of Data Base Studies (AVRADCOM/NASA/Bell)

0 Several-Year Extended Parametric Study Now Starting

0 Failure Mechanisms and Modes

0 Energy Absorption

0 Various Composite Materials

+ Graphite-Epoxy

+ Kevlar-Epoxy

+ Glass-Epoxy

+ Hybrids

+ Advanced Graphite Fibers and Toughened Resins

Fabrics vs. Tapes

0 Cylindrical Tubes

+ Variation of Layup Sequences and Angles

+ Vary Diameters

+ Various Diameter-to-Thickness Ratios

0 Beam and Sandwich Configurations (Cruciform)

0 Static Tests

0 Impact (Drop) Test -- Impact Velocity Variation Effects

0 Scaling Effects

0 Test Specimens to be Fabricated by Bell Helicopter Textron

0 Tests to be Conducted Mainly at NASA-Langley (Static, Impact-Drop, and Impact-Tower)

D. Advanced Composite Airframe Program
(Bell Helicopter Textron and Sikorsky Aircraft under AVRADCOM)

0 Development of All-Composite Airframe Structures for Army Applications: Primary and Secondary Structure

0 Crashworthiness is One Requirement (MIL-STD-1290AV)

0 Two Contractors Selected: Bell Helicopter Textron and Sikorsky Aircraft

0 Advanced Composites for Airframe, Landing Gear, Rotor,...

0 Critical Problems: Attachments, Joints, Fittings, Cutouts

0 Design and Tests of Components: Static and Impact-Drop

0 Tower-Drop Impact-Crash Test of Full-Scale Configuration

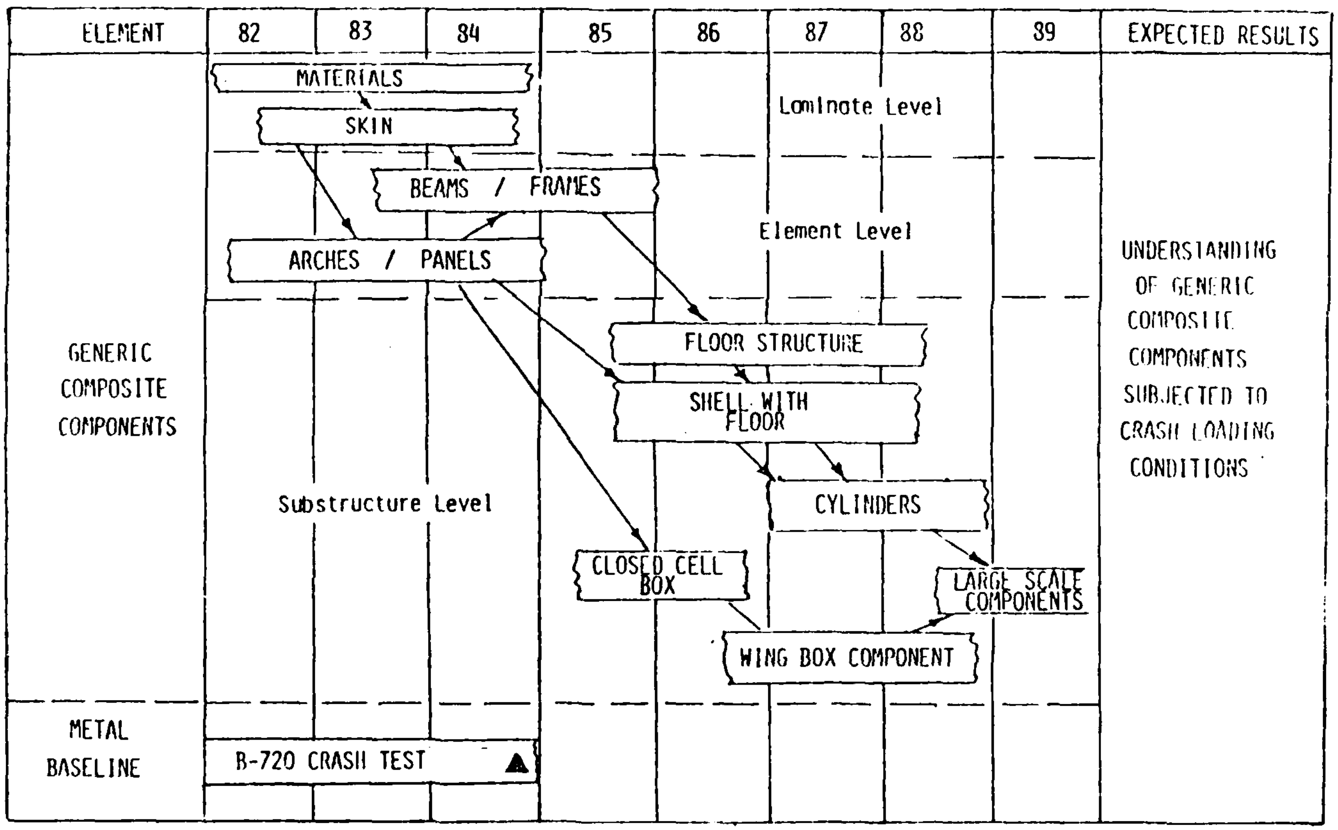
The latter two studies (C and D) are of a longer-range nature. Study D is very broad, and crash response is only one of many facets of that development program [113].

5.4 Transport Crash Research

For transport aircraft, Thomson and Caiafa [2] and Wittlin [21] report that NASA and the FAA are sponsoring studies of transport aircraft crash dynamics by Boeing [116], Douglas [117], and Lockheed [118]. These studies are expected to identify the prevalent potentially-survivable crash scenarios. For each such scenario, the likely sequence of failures and associated structural regions principally involved will be noted. The associated consequences such as fuel tank/line rupture, mass item failure, floor/door deformation, loss of seat integrity, and excessive occupant loads are to be considered [21]. These studies should provide guidance for focusing subsequent crashworthiness development work on those structural and systems regions which most seriously affect occupant survival. The region of the aircraft most immediately involved in many crash scenarios, of course, is the lower crown of the fuselage structure and/or the landing gear and its attachment structure. Hence, the elastic, failure, and postfailure responses of shell/frame/keelson structure of metallic and/or composite-material construction must be understood and the consequences to the occupants held to acceptable limits.

Shown on the next page is a NASA/FAA flow chart depicting a logical sequence of studies on the behavior of composite-material structures subjected to crash loading conditions. These studies commence at the laminate level, proceed to the element level, and go on to the substructure level. In a future time frame, a full-scale crash test of a composite airplane can be expected to take place.

RESPONSE CHARACTERISTICS OF GENERIC COMPOSITE COMPONENTS
TO SIMULATED CRASH LOADINGS



In support of the early stages of that outlined NASA/FAA transport crash response study, at least two research efforts are in progress. These studies are outlined in the following under headings E and F [114,119]:

E. Accident Data Base Studies (by Boeing, Douglas, and Lockheed)

F. Crashworthiness of Composite Fuselage Structural Components (NASA-Langley and Lockheed Aircraft)

NASA/FAA Transport Crash Response Research

E. Accident Data Base Studies (by Boeing, Dougias, and Lockheed)

- 0 Identify Range of Survivable Crash Conditions
- 0 Main Structural Features and Subsystems Affecting Injuries
- 0 Research and Approaches to Improve Transport Crashworthiness
- 0 Identify Test Techniques, Analytical Methods,... Needed to Assess and Evaluate Transport Crash Response
- 0 Preliminary Results
  - + Four Survivable Accident-Condition Categories
  - + Transports: Shallow Descent Impacts are Dominant
    - o Small Vertical Velocity at Impact
    - o Large Forward Velocity at Impact
  - + Structure-Surface Interactions Important for
    - o Rigid Surfaces: Concrete
    - o Compliant Surfaces: Packed or Plowed Ground
  - + Worst Threat is Fuel Spillage from
    - o Main Gear Penetration into Fuel Tank Area
    - o Failure of Wing-Mounted Engine Pylons
    - o Wing Structure Failure
  - + Useful Analysis Tools
    - o Airframe and Subsystems: KRASH for Gross Response and DYCAST for Detailed Response (Improvements Needed for Composite-Structure Analysis)
    - o Occupant-Seat-Restraint System: Use of SOMLA and DYCAST (new code DYSOM)
  - + Variety of Typical Lower Fuselage Configurations
  - + Need Study to Enhance Crash Response Understanding and Behavior of Each Type
  - + Analysis of Occupant/Seat/Restraint/Floor/Subfloor Responses at Various Stations Along the Fuselage

F. Crashworthiness of Composite Fuselage Structural Components (NASA-Langley and Lockheed Aircraft)

OBJECTIVES

- 0 Identify Important Structural Parameters, Structural Response Characteristics, and Potential Failure Modes

- 0 Define Appropriate Test Methods
- 0 Compare Damage Sensitiviey of Composites to Conventional Aluminum Fuselage Structure
- 0 Investigate Graphite-Epoxy and Hybrid Laminates
- 0 Focus on Structural Concepts for Lower Crown of Fuselage

STRUCTURAL PARAMETERS

- 0 Strength, Stiffness, Inelastic Behavior

STRUCTURAL RESPONSE CHARACTERISTICS

- 0 Crash Environment
- 0 Load-Deflection Behavior
- 0 Energy Absorption
- 0 Static vs. Dynamic Behavior

POTENTIAL FAILURE MODES

- 0 Buckling, Delamination, Tearing, Abrasion, Thermal Degradation

COUPON TYPE TESTS

- 0 Tearing Resistance: Aluminum vs. Composite Laminates Out-of-Plane and In-Plane Tearing
- 0 Abrasion Resistance Skin-Stringer and Orthogrid Coupons Against a Concrete Surface
  - + Conditions: Velocity 50 to 100 mph
    Pressure 50, 100, 150 psi
  - + Aims: Wear Resistance of Laminite Skins
    Temperature Effects on Resin
    Compare Results with Aluminum Coupons
  - + Material: Aluminum, Graphite-Epoxy, and Hybrid Laminates

STRUCTURAL ELEMENT TESTS

- 0 Elements of Frame and Keelson Structure (Aluminum Beam vs. G/E Honeycomb vs. Kevlar Honeycomb)
- 0 Failure Mode and Load-Deflection Behavior
  - + Through-Depth Compression: Crushing
  - + Axial Compression
  - + Axial Sheer
- 0 Static Tests and Impact (Drop) Tests

TESTS OF SUBSCALE AIRFRAME COMPONENTS

- 0 Fuselage Skin-Frame-Stringer-Keelson Structure
- 0 Static Tests: Failure Mode and Load-Deflection Behavior

0 Dynamic Drop-Impact Tests: Failure Mode, Load-Deflection, and Energy Absorption Behavior (Measure: Load, Strain, Acceleration, and Deflection vs. Time)

0 Assess Postfailure Behavior of Grillage Structure

At a reasonably early stage in this overall program (summer of 1984), a full-scale B-720 transport crash test is planned. This will permit studies in three crashworthy research areas [2]: structural airframe and seat response, anti-misting kerosene performance characteristics, and cabin fire safety materials testing. The structural airframe and seat response objectives of those studies are [2]: "(a) to define dynamic seat pulse data in the form of acceleration time histories at the seat/floor interface, (b) to measure acceleration time-history data throughout the cabin interior for comparison with nonlinear analytical predictions* of structural behavior and to determine the level of injury by acceleration indices, (c) to determine the accuracy of current flight recorder data, (d) to assess current and improved seat/restraint-system/floor behavior, and (e) to determine structural deformations and failure modes." Both current and new seats and restraint systems could be assessed and compared directly.

In addition to these structural component and structural assembly tests, new seat and restraint systems may be tested and assessed separately or in conjunction with impact tests on proposed composite-structure floor/subfloor load-limiting concepts such as explored, for example, by Carden and Hayduk [107]. Transient response, interaction, failure-mode, and postfailure response data could be obtained to assess the overall concepts and nonlinear transient response prediction methods.

Another important objective of the B-720 transport crash experiment is to provide more comprehensive crash response data than obtained heretofore for conventional metal-structure transports. This information can serve as baseline data against which crash response behavior of future composite-material transports can be compared in the quest for comparable or better crashworthiness.

5.5 Proposed Research

The present review of aircraft crash-response research indicates that composite-material aircraft structures are receiving and will receive increased emphasis in the future. However, selective subscale and full-scale impact crash-response measurements of conventional built-up metallic aircraft structures will be made to form a baseline comparison against which to assess the crashworthy performance of future "replacement vehicles" composed largely of composite materials. This useful role is included in the NASA-FAA research plan [2,11,114,119].

The overall crash-response research plan indicated in the NASA flow diagram shown in Subsection 5.4 is schematic but comprehensive. Thomson and his colleagues at NASA-Langley have given careful thought to the composition,

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* Such as provided by KRASH and/or DYCAST, for example; validating and upgrading of these prediction methods is also a goal.

succession, and appropriate timing of work to develop comprehensive information on the crash-response behavior of composite-material structural elements and structural assemblages. Detailed plans for that entire research program have not been seen, and the present reviewers do not presume to advise those very capable and knowledgeable NASA/FAA researchers and planners. Rather we wish to cite a few matters that are believed to merit study, although these and other more important items may already be included in the NASA/FAA research plan. Those matters are noted briefly in two categories (a) experimental structural studies and (b) prediction method development in Subsections 5.5.1 and 5.5.2, respectively.

5.5.1 Experimental Structural Studies

The assistance and advice of transport and general aviation (GA) airframe manufacturers such as Boeing, Douglas, Lockheed, Lear,... should be sought to identify the principal structural elements and configurations which their experience and design studies show most likely to be employed in future composite-material transport and GA aircraft. This should include representative stations all along the fuselage from the nose to the tail, including the wing box and landing gear support and load transfer structure.

This information could serve to set priorities on and initially emphasize detailed failure and postfailure studies of the most important structural elements and subassemblies. Recommended material composition and layups for beam, keelson, frame, or other basic elements should be sought since design and feasibility studies will have led to a narrowing of the multitude of possibilities offered by composite-material construction. Based upon this information, one could select a small set of high priority configurations for subsequent construction and testing.

For each configuration selected*, it is proposed that subscale structural assemblies be constructed and tested first in vertical impact tests to determine the modes and sequence of impact-induced structural failures. A second set of impact tests should be conducted employing a representative ratio of horizontal-to-vertical impact velocity with impact against a "concrete runway" surface -- again to assess the failure modes and sequences associated with these conditions. In all cases detailed observations and transient response measurements should be made. Based upon these results and observations, a subsequent set of static tests should be carried out on either the "same" structural assemblage or upon selected portions (if feasible) of that assemblage to evaluate and compare these failure modes with those observed in the two dynamic test conditions, and to obtain postfailure load-deflection and other structural-behavior data. These results should indicate the nature and extent of subsequent static-test studies which may be useful. These impact tests and static tests will provide transient response and mechanical-behavior data of intrinsic value but also information which can guide the analyst in deciding the minimal necessary level of structural modeling required to permit realistic predictions of nonlinear transient structural response of selected structural regions or assemblages. The necessity of developing more comprehensive finite elements or the adequacy of employing relatively simple finite elements in conjunction with the hybrid procedure (and guidance for selecting an effective hybrid procedure)

* Appropriate account must be taken of much prior experience by NASA, AVRADCOM, Bell, Lockheed,...to select crashworthy rather than fragile materials/configurations.

should become evident from these test results and subsequent analysis comparisons (using DYCAST and KRASH, for example).

It is recommended that studies of the type outlined above be carried out on each of several "typical fuselage section" configurations to cover in a subscale laboratory fashion all of the important regions of the fuselage, wing-fuselage, etc. which can undergo important crash-induced failure and postfailure responses. In selected instances (when timely), seat/occupant/restraints and attachments should be included and their responses measured. Subsequent analysis should be carried out to validate and upgrade transient response prediction procedures.

With the proposed sequence of impact and static tests of (a) structural assemblages and (b) structural elements a fund of failure and postfailure information will be generated for composite-material combinations and configurations which are most likely to be employed in future transport and GA aircraft. This data base should be valuable for conducting design studies to meet specified crashworthiness requirements. Also, this experience will lead to additional structural/material concepts for improved crashworthiness.

Also, when timely, similar structural-assemblage "sliding-impact" tests against packed earth should be conducted to uncover any different modes of response and failure produced in these composite structures by these impact-interaction conditions.

5.5.2 Prediction Method Developments

Restricting attention to methods for predicting transient nonlinear structural response of aircraft structures produced by impact or crash loads, it appears reasonable to assume that essentially two types of analyses (or computer programs) will serve as the prediction workhorses. The conventional-lumped-parameter/hybrid method as represented by program KRASH will continue to provide useful overall-response preliminary-design information because of its comparative economy and simplicity. For detailed transient response predictions, the finite-element procedure as represented typically by the DYCAST program will likely find much but selective use; because of its higher fidelity modeling capabilities, this program can provide very detailed transient response information but the computational expense involved tends to limit its use to certain selected portions of the entire structure.

In applications to composite airframe structures, KRASH has been demonstrated to be effective [3,21] but its effectiveness depends heavily upon the selection of an appropriate lumped-parameter model of the structure involved. That selection requires much skill and judgment on the part of the analyst; this in turn requires first-hand modeling-and-application experience with KRASH and evaluations of predictions versus transient structural response measurements. It is urged that such studies continue as the NASA/FAA program of impact and crash experiments proceeds. That experience will produce improved skill and guidelines for appropriate structural modeling and will also suggest (a) where in the structural model that the prescribed nonlinear hybrid load-deflection behavior needs to be provided and (b) the nature and properties of that hybrid behavior. Various types of composite arrangements for fuselage frame, skin-frame, and keelson structure may require different hybrid properties. Carefully selected static-test experiments to produce failure and postfailure structural deformation patterns closely simulating those observed in crash-impact tests will be needed to generate the fund of hybrid-station mechanical-behavior data to represent the mechanical behavior of typical generic composite configurations. As this data base grows, the analyst will be able to use KRASH more effectively for preliminary design studies.

With respect to the more refined finite element transient nonlinear structural response prediction methods, it should be noted that the finite-element structural model results in a set of ordinary nonlinear differential equations of motion which can be solved timewise in small increments Δt in time by the use of an appropriate finite-difference operator, either explicit or implicit. When the finite-element model consists of a relatively small number of degrees of freedom (DOF), it is most efficient to solve those equations timewise by using an explicit operator such as, for example, the timewise central-difference operator. However, explicit operators when applied to either linear or nonlinear systems require that Δt be sufficiently small; otherwise, the calculation will blow-up from (unavoidable) error growth. Hence, when the finite element model has a great many DOF, the required Δt size is so small that the computational expense involved in carrying out the calculation for the necessary amount of total time becomes prohibitive. In such cases, timewise implicit operators are used since such operators permit one to use much larger values of Δt without computational blow-up.

When timewise implicit methods are used to solve nonlinear transient structural response problems, one of two approaches is used commonly. In one case, the internal nonlinear loads at a given time instant t_n are estimated by extrapolating known internal nonlinear loads at earlier time instants t_{n-1} and t_{n-2}; the result is an approximation of the proper equations, and the solution can be carried out in a straightforward noniterative fashion [120]. However, the solution is guaranteed always to be incorrect. But if Δt is not "too large", the solution accuracy may be acceptable for engineering purposes. If the entire solution is repeated by using a fixed Δt which is half as large as the former Δt, one can conclude that a "converged" solution has been found if both predictions agree. If not, the process can be repeated until a converged result is obtained. While each of these calculations is comparatively inexpensive, the overall computational expense can become large if many repeat calculations are needed to reach convergence. This "efficient but uncertain trial-and-error procedure" can be circumvented by solving the correct rather than the approximate nonlinear equations at each time instant.

To solve the correct nonlinear equations at each time instant with implicit methods requires that iteration be carried out to convergence at each time instant. Here also if severe nonlinearities are present, certain iteration procedures will fail to converge for a given Δt size. For present purposes let it suffice to note that recent studies have shown quasi-Newton methods to be both effective and efficient [110,111]; to date these are the most effective methods known for solving nonlinear transient structural response problems. The documentation seen on the workhorse DYCAST program suggests that implicit solutions with iteration are carried out, but the procedure used and the convergence criteria employed are unclear.

It is recommended that a study be made of the feasibility of adapting the BFGS version of the quasi-Newton method [111] to DYCAST as a possible means of enhancing its efficiency and effectiveness; this is a powerfully convergent and efficient method. Of course, in all of these methods the time step size Δt must be small enough to permit following the response history details of interest. Details of interest to the analyst may be missed if the Δt employed is too large.

Also, although DYCAST contains several timewise finite-difference operators (some with fixed and others with variable time step size Δt) which the analyst may select for use, a more recent variable time-step-size procedure developed by Hibbitt appears to be very attractive. Hibbitt [121] has proposed a scheme to change the time step size in an exceptionally effective manner as the solution proceeds so that overall accuracy may be maintained while eliminating unnecessarily (and uneconomically) small Δt steps whenever possible (i.e., during periods of slowly varying response). His procedure makes use of a modified Newmark operator devised by Hilber and Hughes [121]. This approach together with BFGS iteration has been demonstrated to be quite effective [110]. It is suggested that the possible adaptation of this procedure to DYCAST be explored (if not already done).

SECTION 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The present study was intended to consist of a review of the state of the art of aircraft crashworthiness work both experimental and theoretical, but restricted to considerations of severe structural response aspects. Considerations pertaining to fuel system protection (and fires) and to emergency evacuation systems were to be omitted.

Principal attention, therefore, was given to examining the state of experimental investigations and of theoretical methods for predicting severe transient structural responses of (a) conventional built-up metallic aircraft structures and (b) the newer composite-material structures. This information was sought by searching the literature, by contacting personnel from involved governmental agencies and the airframe industry, and by visits to the FAA Technical Center, NASA-Langley, AVRADCOM, AFML and ASD, within the confines of the available time and effort for this project.

As a result of these contacts and visits, various reports and papers on past research of the crash responses of helicopters, general aviation aircraft, and transports were furnished to us for study by those contacted individuals. In addition to reports on a succession of specific experimental and theoretical investigations on aircraft crash response, summary state-of-the-art papers or reports on crashworthiness were provided. Most of this information applies to aircraft of built-up metallic construction, but two of these summaries included information on both past work and planned work on the crash responses of composite-material aircraft structures. Information in this latter category, however, appears to be quite limited but is growing.

In personal visits to, telephone discussions with, and/or written information from the FAA Technical Center, NASA-Langley, AVRADCOM (Ft. Eustis and NASA-Langley), and Bell Helicopter Textron personnel, some information was obtained on both current and planned research on the crash-impact responses of advanced composite airframe structures.

The results of this information collection-and-study are given in Sections 2 through 5 of this report.

6.2 Conclusions

The current state of available aircraft crash response information is described in a very concise but comprehensive manner in the following categories by the indicated documents:

General Aviation Aircraft: Ref. 11 by Thomson and Goetz
Ref. 2 by Thomson and Caiafa

Helicopters: Ref. 20 (and/or Ref. 3) by Cronkhite et al
Ref. 21 by Wittlin

Transports: Ref. 2 by Thomson and Caiafa
Ref. 21 by Wittlin

General Aviation Aircraft

Crash response research for general aviation (GA) aircraft has been led and sponsored by the FAA and NASA since the early 1970's. Many full-scale crash experiments have been conducted on GA type aircraft at the NASA-Langley tower impact facility (Impact Dynamics Research Facility). Detailed measurements of strains, deflections, and accelerations (as well as high-speed photographic observations) were made at many locations in each aircraft. In many cases, instrumented dummy occupants also were used. This has led to an understanding of the principal modes and patterns of failure and postfailure response for these types of metallic and built-up metallic aircraft structures. Subsequent static tests on these principal structural components has provided failure and postfailure load-deflection data which has been employed empirically in nonlinear transient response computer programs to carry out theoretical-experimental correlation studies.

Since these experimental measurements and comparisons with field accident data indicated that the g-forces measured in the cabin area were in most cases well above human tolerance levels even though the livable volume and structural integrity of the cabin area had been maintained, a need was seen to develop modified structural concepts to permit more uniform and controlled crushing of the subfloor and better vertical-seat-stroking load attenuation mechanisms. Subsequently, an extensive series of subfloor concepts was designed, built, and tested. Static load-deflection crush tests as well as drop-impact tests on full fuselage section, subfloor, seat, and simulated occupant configurations were conducted at NASA-Langley as reported by Carden and Hayduk [107]. This work has demonstrated the effectiveness of a variety of subfloor concepts for reducing the g-forces in the occupant pelvic area. The development and validation of these subfloor concepts represents a significant improvement in potential crashworthiness of GA aircraft.

Subsequent comparisons between transient response measurements for these fuselage-subfloor-seat-occupant configurations and predictions from (a) the lumped-mass program KRASH model and (b) the finite-element DYCAST model demonstrated reasonably good theoretical-experimental agreement. However, the more refined DYCAST model and calculations provide much more detailed and realistic transient response histories than does program KRASH. These complementary prediction capabilities, KRASH and DYCAST, have been developed to a very useful stage but further development of each will be needed to deal with future types of composite-material airframe structures. It should be noted that various of these subfloor concepts consist of combinations of metallic and non-metallic materials in various arrangements; static load-deflection crush tests were carried out both to assess the performance of a given concept and to provide failure loads and nonlinear load-deflection data needed as input into both the KRASH and the DYCAST program. A similar information generation-and-use procedure is anticipated when future composite-material configurations are investigated. In this way an expanding data base will be developed for future crashworthiness design and analysis purposes.

Load-limiting seats and seat-attachment devices have been designed, built, and tested; the transient response results measured in crash deceleration simulations have been compared with those for "unmodified designs" as reported by Fassanella and Alfaro-Bou [122]. Significant improvements have been demonstrated. Also described in Ref. 122 is an FAA-funded computer program called SOMLA which models an aircraft seat, an occupant, and a restraint system. This 3-d finite-element seat and lumped-mass/spring/damper occupant model was used to predict occupant response in a seat-occupant drop test, with excellent experimental-theoretical comparisons. For a more versatile and comprehensive prediction capability, SOMLA is being combined with the finite-element DYCAST program; all indications are that this will provide a very useful and reliable design tool.

Helicopters

The U.S. Army Research and Technology Laboratories (AVRADCOM) and its predecessor organizations at Ft. Eustis, Va. have been conducting crashworthiness research since the late 1950's. This work has led to the development of a set of aircraft crashworthiness requirements [18] and to the 5-volume Aircraft Crash Survival Design Guide [13-17] which is regarded widely as the bible for the crashworthiness design community. Crashworthiness design principles and guidelines spelled out in Refs. 13-17 have been applied and have increased significantly the crashworthiness and occupant survival of Army helicopters and light aircraft.

Also, AVRADCOM was the first organization to investigate at some length the use of composite materials in airframe structures and their behavior in crash situations. References 3 and 20 summarize those developments. Various airframe elements and components consisting of composite materials have undergone static and impact testing to assess their failure, postfailure, and energy-absorbing behavior.

AVRADCOM is sponsoring a very comprehensive development activity called the Advanced Composite Airframe Program [113] in which two airframe manufacturers Bell Helicopter Textron and Sikorsky Aircraft are playing parallel leading roles. In this ACAP activity, aircraft crashworthiness is only one of many design objectives and requirements in developing all-composite airframe designs.

A systematic series of studies following the recommendations of Ref. 3 to assess parametrically the behavior of various composite-material structural concepts for helicopter fuselage structure in both static and impact situations, as noted under item A in Subsection 5.3, has been carried out and will be reported upon shortly. Since the amount of essential experiments and data available to reveal the failure and postfailure behavior of the many composite-material configurations and arrangements of practical interest is still very small, an extended program of experiments, as outlined under item B in Subsection 5.3, is currently being conducted with emphasis on items with helicopter applications. A more general data base extension to take place over the next few years is outlined under item C of Subsection 5.3.

It is apparent that a very good start has been made in obtaining failure, postfailure, and energy absorption data for various structural elements composed of composite materials. Much remains to be done. As the current outlined program proceeds, useful avenues along which to extend these investigations will become evident; the variety and complexity of potentially viable materials and configurations to provide enhanced crashworthiness is too vast to encourage speculation on useful directions except in very general terms. Innovative structural concepts which provide load limiting behavior, a large energy-absorbing capacity before collapse, and the use of hybrid material layups with enhanced toughness resins are self-evident goals.

Transports

In the mid 1960's, the FAA conducted full-scale crash tests [2] on two different transport aircraft: (a) to obtain crash environmental data, (b) to study fuel containment, and (c) to collect data on the behavior of various components and equipment aboard the airplane.

In 1984 the FAA and NASA are proposing to crash a remotely-piloted Boeing B-720 into the ground to simulate a survivable crash landing; the principal objectives [2] are to: (1) corroborate analytical predictions, (2) test crashworthy design concepts, and (3) verify the performance of anti-misting kerosene additives. The cabin interior will be fully instrumented [2] and will contain both standard and crashworthy seat designs with fully instrumented anthropomorphic dummies. Crashworthy structural floor features will be assessed during the monitored crash sequence. The test objectives focus upon (i) structural airframe and seat behavior, (ii) the performance of anti-misting kerosene, and (iii) characterization of cabin hazards created by external fuel fire; these are elaborated upon more fully in Ref. 2. The structural and occupant response data to be obtained in this test are to serve as baseline crash response information associated with a conventional metallic airframe structure -- for comparison in the future with structural response data from "a composite materials/structures replacement" designed to meet the same basic specifications as the older design but to exhibit crashworthiness behavior at least the equal of its older counterpart with little or no increase in weight and with acceptable cost.

Thomson and Caiafa [2] and Wittlin [21] describe the current and planned program of transport crash dynamics research being conducted cooperatively by the FAA, NASA, and industry to develop technology for improved crashworthiness and occupant survivability in transport aircraft. Aside from the baseline transport crash response data to be obtained for a conventional (B-720) transport, emphasis is given to investigating the behavior and effectiveness of composite-material transport airframe structures in future designs. In pursuing this area, the past information and experience developed in the general aviation and helicopter crash dynamics programs are being taken into account. It is noted [2] that transport aircraft have somewhat different features from those of GA aircraft and helicopters with respect to fuel containment, multi-occupant seat and floor behavior, composite crash response, and multi-occupant egress.

Under the FAA/NASA transport aircraft crash dynamics research program, Boeing, Douglas, and Lockheed-California are conducting studies of past aircraft accidents to identify the principal categories of potentially survivable crash scenarios and conditions as a focus for subsequent investigations [2,21]; four categories and the associated impact conditions have been identified. Also, these airframe designers and companies are seeking to identify the various typical structural configurations and arrangements of composite-material structures likely to be employed at various fuselage and wing stations; the overall objectives and preliminary results obtained are outlined under item E on page 106. In parallel and in collaboration with this work, NASA and the FAA have laid out a composite materials/structures test program to investigate the response characteristics of a succession of structural components and assemblages to simulated crash loadings as indicated in the NASA/FAA planning chart shown on page 105. Some of the facets and objectives of this part of the FAA/NASA program are indicated under item F on pages 106-108.

As this FAA/NASA/industry transport crash dynamics research program proceeds, data and experience on the crash responses of structural elements and assemblages comprised of various different composite materials and combinations thereof, honeycomb structure, etc. will point the way to ever more effective structural concepts and materials for coping with crash conditions efficiently. The basic FAA/NASA plan is a very logical and orderly one, and can be expected to produce a valuable fund of structural behavior and design information which can be applied to reduce crash hazards and achieve a high level of crashworthiness in future composite-material transport aircraft. A very important ingredient in achieving these goals will be the close and continuing involvement of and collaboration between the airframe industry and the FAA/NASA team in all aspects of this research: experimental, analytical, and design. In addition to developing necessary basic data, this collaboration should lead to an effective focussing of effort on design and material concepts which will find practical application in future transport aircraft.

Summary Comments

The available information on current programs of experiments to investigate the failure, postfailure, and energy absorbing behavior of composite-material structural elements and assemblages under both static and simulated crash conditions has been outlined under items A, B, C, and D in Subsection 5.3 and under items E and F in Subsection 5.4. Aside from Refs 2 and 21, no progress or status reports have been received to provide an up-to-date assessment of progress and problems encountered in those studies. The most meaningful and authoritative recommendations for subsequent necessary crash response work will come from the investigators who are actively carrying out and monitoring those experiments. These include personnel at:

a. Bell Helicopter Textron
b. Sikorsky Aircraft
c. Lockheed California
d. AVRADCOM, Ft. Eustis
e. AVRADCOM at NASA-Langley
f. NASA-Langley Structures Division
g. NASA Langley Process/Applications Branch, Materials Division
h. FAA Technical Center

among others. R. Thomson of the NASA-Langley Research Center, C. Caiafa of the FAA Technical Center, and R. Burrows of AVRADCOM, Ft. Eustis, Va. have provided strong leadership in planning and sponsoring crash response research work. Close collaboration and cooperation amongst these individuals and agencies as well as amongst their contractors will be effective in the orderly and rapid development of crashworthy technology for future composite-material aircraft.

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